Escola de Camins
Escola Tècnica Superior d'Enginyeria de Camins, Canals i Ports
UPC BARCELONATECH

Structural Lightweight Aggregate Foamed Concrete

Treball realitzat per:

Jessica P López Arias

Dirigit per:

Miren Etxeberria Larrañaga (UPC)

Yunping Xi (UCB)

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DEDICATION

To my mother, for all her love and support in everything necessary to fulfill my goals as a person and as a student.

To my sister, for her confidence, whom I always find when I need her, and because at her side work is less work.

To both, once again, thanks for have never left my side.

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ABSTRACT

Foamed concrete has been used historically as insulation material due to his low density. The goal of this research is to improve this lightweight material so they can be used as insulation materials as well as structural material, with sufficient strength, finding an optimum balance between mechanical and insulation properties so that the material can be used as structural and insulation material for building envelops.

As it is well known, all the engineering works requires a resistant and compact concrete. However, in the standards constructions and rural buildings, for example, its required materials and concretes with a good thermal insulation capacity. The thermal insulation capacity of a building material increases as decreases its weight per unit of volume, i.e., the insulating ability of a material increases as it increases the porosity of the material. Therefore, the current concrete, whose advantages, from the technical point of view, resides indeed in its compactness, cannot represent a solution such as insulating material. That is why, the most interesting feature of the conventional concrete must be replaced in order to achieve a porous concrete. This porous concrete or lightweight concrete is a kind of special concrete whose main characteristic is the porosity. To achieve this porous concrete, it is necessary to make modifications, since the rules that govern the composition of the conventional concrete cannot be applied without further for the composition of the second type of concrete, the lightweight concrete.

There exists different procedures to carry out in order to achieve a low specific weight material with sufficient strength. The different procedures differ from each other by the type of aggregate used in the mixing process, for example, it is possible to use directly lightweight aggregates, conversely, to use regular aggregates with standard density in combination with measures that ensure a special concrete porosity. This research is focused on finding a suitable procedure between both ways of achieve foamed concrete with an adequate resistance.

The choice of one of the procedures mentioned for the obtainment of lightweight concrete creation depends entirely in the available aggregates and the aim of the research. It is important to mention that there is not an ideal granulometric composition applicable to the aggregates destined to lightweight concrete. Therefore, there are many suitable granulometric compositions for lightweight concrete.

This research focuses on the rules governing the manufacturing process of the lightweight concrete in order to achieve an adequate composition of this and, also, to bring the structural characteristic to this material.

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CHAPTER I. INTRODUCTION

1.1. Foreword

This project is the compilation of a five months research at *University of Colorado Boulder* (USA) in collaboration with U*niversitat Politècnica de Catalunya* (SPAIN). The Construction Material Department of both universities were keeping up to date of the different investigation phases and gave support in everything that were necessary for the successful accomplishment of this project.

1.2. General aspects

This document is the result of an experimental process that was carried out with the aim of achieved a material made of lightweight aggregates, cementitious material, water and sometimes chemical admixtures that constitute an insulation material, self-compacting, flowable and structural material with sufficient strength that allows being used as structural and insulation material for building envelops. This material will be create based on the foamed concrete bases. However, the necessity of this research emerge from the initiative to create a mixture that replaced the natural aggregate by lightweight aggregate.

Structural lightweight aggregate concrete is an important and versatile material in modern construction. It has many and varied applications including multistory building frames and floors, bridges, offshore oil platforms, and prestressed or precast elements of all types. Many architects, engineers, and contractors recognize the inherent economies and advantages offered by this material, as evidenced by the many impressive lightweight concrete structures found today throughout the world [1] [2]. Structural lightweight aggregate concrete solves weight and durability problems in buildings and exposed structures. Lightweight concrete has strengths comparable to normal weight concrete, yet is typically 25% to 35% lighter. Structural lightweight concrete offers design flexibility and substantial cost savings by providing: less dead load, improved seismic structural response, longer spans, better fire ratings, thinner sections, decreased story height, smaller size structural members, less reinforcing steel, and lower foundation costs. Lightweight concrete precast elements offer reduced transportation and placement costs [3] [2].

This research work was conducted in three different stages in order to analyse the applicability of lightweight aggregates in the production of foamed concrete using air-entraining admixtures. Stage 1 consisted in defining the optimum mix proportion of conventional foamed concrete made with Portland cement, water, air entrained admixture and natural fine aggregates, achieving the specific requirements defined by ASTM in fresh and hardened state. Stage 2 measured the influence of the lightweight aggregate on fresh and hardened state by defining different properties of the foamed concrete material. Lightweight aggregates were used in 10%, 20%, 50% and 100% substitution of natural fine aggregates volume defined in conventional foamed concrete mixture in stage 1 and the obtained results were compared to those of conventional dosages. The optimum mix proportions, according to specific requirements defined by ASTM, of foamed concrete made with different percentages of lightweight aggregates were determined.

Once a suitable mixture is found in stage 2, the stage 3 is based in produce beams with the best mixture obtained for making fracture test in order to study its behaviour.

1.3. Targets

1.3.1. General targets

The purpose of this project is the analysis of the lightweight aggregates applicability like main constituents for the production of foamed concrete.

1.3.2. Specific targets

1. Define a control dosage that gives suitable fresh and hardened state properties with just the use of natural aggregate.
2. Study of the behaviour in both states of the foamed concrete mixture made with different proportions (10, 20, 50 and 100 %) of lightweight aggregate to find the optimum percentage to substitute for natural aggregate.
3. Study of the best mixtures obtained in previous sections with fracture test.
4. Verify all the optimum dosages achieved.

1.4. Structure of the master's thesis

This master's thesis is structured in six different chapters in order to provide the understanding of this research that have been performance.

The experimental process was divided in three different stages, containing many photos for the purpose of increase the comprehension quality because when talking about different types of materials is challenging to imagine it just by reading.

CHAPTER I. Introduction

In this chapter is introduced abbreviatedly the main motivation for the development of this experimental project. It is detail the different objectives and gives a brief description of the project structure.

CHAPTER II. State of the art

This chapter is the literature review of the different parts of the mixture components and it is explained all the current useful information about foamed concrete and lightweight aggregates. Previous researches are also referenced because have been the guidelines of this experimental process and the examination of the obtained results.

CHAPTER III. Materials and experimental process

In this chapter is described all the components that had been used, with their main characteristics, to produce foamed concrete with natural and lightweight aggregates. It is also explained the experimental and manufacturing process, and the testing procedure in both fresh and hardened state.

CHAPTER IV. Mix proportion determination

In this chapter are indicating the dosages that have been used for produce foamed concrete and the attributes of the manufactured material in the two different states (fresh and hardened state).

CHAPTER V. Optimum dosages

In this chapter, having had a good mixture from the previous chapter, the same dosages were produced for fabricating beams and being able to cast those for fracture test procedure.

CHAPTER VI. Conclusions

In this chapter are exposed the obtained conclusions of this research, and it is suggested possible future research lines.

CHAPTER II. STATE OF THE ART

As a first step of this project is necessary to provide a comprehensive insight into the foamed concrete and all the possible applications of this construction material. For this, a review of almost all the different properties and fabrication techniques of the foamed concrete are going to be done in this part of the research. First, the material properties of the foamed concrete will be analyzed and then and expansion of the possible improvements with foamed concrete, defining the design proportions and the selection of the different constituent materials in order to improve the performance of lightweight concrete in fresh and hardened state.

2.1. Existing problem

On April 20th 2010, an explosion and fire happened on the BP Deepwater Horizons oil platform in the Mexico Golf. This catastrophe caused an enormous ecological and economical disaster. Many investigations led by Chevron, Halliburton and the National Commission of the United States found out that a dysfunction of the pressure limiting caused the accident. However, in order for the both hydrocarbon gas and liquids to reach the plug, they had first to go through the paste of cement in the well. This cement is a slurry of foamed cement, that means a fluid, light and easy material to pump. Foamed cement is made of cement, water, fine particles like sand or fly ashes, additives (foaming agents) and nitrogen gas that generate the internal bubbles. Analysis showed that the foamed cement used by the company was unstable because of the use of bad additives. Moreover, the tests realized on samples 24 hours after the manufacturing process revealed a null compressive strength [4].

Nowadays, there are still many areas to explore regarding the foamed cement.

2.2. Introduction

Traditionally, foamed concrete has been commonly used in construction all over the world in order to reduce dead loads on the structure and foundation due to its low density. It has also been used due to contribute to energy conservation, and lowers the labor cost during construction. In the last decades, there has been a lot of improvements in applied technologies as new equipment and new chemicals (superplasticizers, foaming agents, etc.), that have permitted the study and research of foamed concrete in order to understand and simplify their usage in all the possible applications, as the structural ones. All these progresses has contribute to the use of foamed concrete in a larger scale, and these leads in foamed concrete as an economical solution for lightweight construction material and also for some different structural members [5].

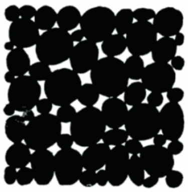
Foamed concrete has been classified as a lightweight material, which densities values range from 400 kg/m^3 to 1850 kg/m^3. These low densities are due to the creation of air voids in the mixture from foaming agents which gives the properties of high flowability, good thermal insulation material and helps to reduce structural dead loads in construction, as it has been said before. Therefore, lightweight concrete is a material with low specific weight. Inside the different range of density standards values, it is possible to make differentiations, more deeply, there are three different lightweight concrete divisions between this range of values (400 - 1850 kg/m^3) [6]:

- Special lightness and high thermal insulation power concrete with moderate strength capacity, whose specific weight varies from 400 to 800 kg/m^3.
- Thermal insulation lightweight concrete, with medium strength, whose specific weight varies from 800 to 1200 kg/m^3.
- Lightweight tough concrete with limited thermal insulation power, whose specific weight varies from 1200 to 1850 kg/m^3.

These different values of low specific weight can be achieved by three different procedures:

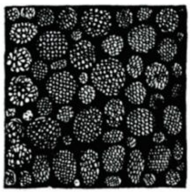
1. By using lightweight aggregates with real low density.
2. By using aggregates with regular density values in combination with measures that ensure a special concrete porosity.
3. By combining the 1st and 2nd procedures.

When it is carried out the first procedure, where the aggregates that conform the concrete have real low specific weight, it is created an immediate reduction in concrete density. This procedure is used in the manufacturing process of lightweight concrete with organic aggregates such as sawdust, wood shavings or wood wool. However, the most commonly used is the second procedure, in which there are different ways to achieve the concrete porous structure:



Lightweight concrete with interstitial pores: using compact stone aggregates, like natural sand, gravel or crushed gravel, but with a special granulometric structure that by limiting the amount of binder it is possible to form holes between the grains

Figure 1. Interstitial pores



Lightweight concrete with pores in the grains: for this is possible to used aggregates of porous stone (natural pumice, crushed brick porous slag, extensive clay, etc.) of any granulometric composition. In this case, the aggregates are wrapped in the cement paste or in the mortar that coat them completely Figure 2.

Figure 2. Pores in the grains

Lightweight concrete with stacking porosity: it is the porous aggregates used to get the lightweight concrete with pores in the granules, which have a specific particle size and are agglomerates with so limited amount of binder that there are also stacking pores or interstitial pores between the grains Figure 3.

Figure 3. Stacking porosity

Lightweight concrete that are part of the carbonated and foam concrete: the pores produced are not interstitial pores neither grains pores. The binder paste and aggregates grains creates an artificial cellular structure Figure 4.

Figure 4. Swelling pores

The third procedure is the selection of organic aggregates with reduced real specific weight that then they flock, and creates lightweight concrete with pores in the grains or lightweight concrete with stacking porosity. The election of one of the three procedures just already mentioned depends entirely in the availability and the goal of the project.
Some researchers has also found that foamed concrete can be characterized with superior properties a part from a low density material. The high porosity creates micro-structural cells in the structure that enhance the fire resistance, the sound absorbance and thermal conductivity. That is why an entire explanation of all the different applications of the foamed concrete are mentioned below.

2.3. Application

Foamed concrete has found applications in civil and structural engineering areas [7], [8] due to the cost-effectiveness (for repair and rehabilitation), ease of production and mainly due to his main special property, the low density [9].

Its use has become popular worldwide for their specific characteristics and for being a cost saving material, but in each different place, a different application has been found. Its use has spread in regions that suffers adverse weather, like hurricanes and earthquake. In Canada, due to a cost increase of other lightweight materials, foamed concrete has been used for tunnel annulus grouting, flowable fills and in geotechnical applications. In The Netherlands, lightweight aggregate was used as road sub-base in order to decrease the dead loads, as main material for bridges abutments due to the significant decrease in the foundation size and the walls thickness. In the Middle East, foamed concrete, due to its lightweight nature is an appropriate material to reduce the adverse effect of the earthquakes, and has also become a suitable material to reduce the negative effect of the changing temperature due to the high thermal insulation capacity [10].

2.3.1. Backfill

Foamed concrete can be used as backfill, void fill, and utility bedding instead of conventional compacted fill. Since compaction is not required, the trench width or excavation size required can be minimized. When the backfill is made against retaining walls the lateral pressures exerted by the backfill fluid should be considered. When the hydrostatic pressure fluid is considerable, the material must be placed in layers allowing each to harden before applying the next. According to ACI 229 [11], [12], compressive strength of a well compacted soil ranges from 0.3 to 0.7 MPa, so its suggest that the compressive strength minimum requirement higher than 0.7 MPa.

2.3.2. Structural backfill

Depending on the resistance requirements, lightweight concrete can be used as a support for foundations. When used as structural backfill, the compressive strength, according to the ACI 229 [11] and depending on the design requirements the ranges could be from 0.7 MPa to 8.3 MPa [13].

In the case of weak soils, foamed concrete can distribute the structure load over a larger area. For layers that are not level or not uniform under foundations, this material can provide a surface that is level and uniform, and can also reduce significantly the required thickness because of their strength.

2.3.3. Thermal insulation

Foamed concrete is applied where thermal insulation conditions are required. Examples include placing this material in soils adjacent to geothermal wells. Foundation soil adjacent to power plants with combustion engines, various industries production plants among others. For all of these applications foamed concrete with very low density is of special interest.

2.3.4. Pavement base

Foamed concrete can be used for bases, sub-bases and leveled subgrades. The mixtures can be directly emplaced from the mixer truck to existing curbs that would act like confiners. When it is necessary restoring a service road in a 24 hours period time, its suggest using foamed concrete with compressive strength higher than 1.5 MPa [13].

2.3.5. Bedding pipeline

Foamed concrete due to the high flowability behaves excellently as backfill material for pipelines, electrical services telephony and other types of conduits. Material characteristics allow even fill cavities in the pipe providing a uniform support.

The filling fluid may be designed to provide resistance to erosion under the pipe, acting as a support bedding which also prevents water appearance between the pipe and the bracket.

Coating the entire duct also serves as future protection for the conduit. If excavate in the pipe vicinity, the apparent change material between foamed concrete and the field alert the existence of a pipeline.

2.3.6. Erosion control

Foamed concrete resists erosion better than other types of backfill. The test results set forth in ACI 229 [11] that was comparative tests with sandy and clay soils, showed that exposing the water at a speed of 0.52 m/s, has better behaviour both in the amount of losses material and suspended material.

The material of this study is used for protecting embankments and dissipation energy works to prevent the displacement of rocks and prevent erosion. This material is also used to backfill voids under the pavement, sidewalks and other structures where the natural soil or granular cohesive and non-cohesive fillers are eroded.

2.3.7. Other applications

Other typical usage of foamed concrete are used under concrete paving, to prevent frost heave in roads, to insulate shallow foundation systems and placements, to prevent frost heave under pile caps and frost jacking of shallow piles. It is also used as a grout to fill abandoned pipes and as backfill under buried oil field modules, to decrease the temperature under hot oil tanks and the tank support and to fill voids under slabs and to reduce the thermal stress and the thermal gradient in hot concrete pits and thus insulate shallow [14].

2.4. Materials

Foamed concrete are based in the basic construction materials plus some additional components. The basic components are cement, aggregates and water. The supplementary materials could be different kinds of additions as, fly ash, fibers, etc.

2.4.1. Binder

The most common binder material in construction, and also for foamed concrete, is cement. There are different types of cement that can be used for foamed concrete creation, as Portland cement, which can be the regular one or the fast hardening. There also exists calcium sulfoaluminate or high alumina cement, but these last types are not as common as the first mentioned above.

For the improvement of conglomerate, is possible to use additional materials as fly ash, silica fume or lime in partial replacement percentage between 10% and 75%. The decision of choosing one type or another of the supplementary materials is based on the type of improvement to be achieved, or the desirable properties, due to each material itself contributes to give some properties, and the result leads in, for example, a development of the mix design consistency and long, or short, term strength.

2.4.2. Water

Water is a basic component of the concrete, its requirements and the water content depends on the consistency, uniformity, constituents of the mixture, admixtures used and the stability of the desired mixture [15].

Generally, the water/cement ratio should be between 0.4 and 1.25. The British Cement Association [15] define for foamed concrete a water/cement ratio between 0.5 and 0.6, although, the proper amount of water should be defined by analyzing the consistency in the experimental phase, ensuring that the workability is acceptable. It is necessary to acquire an adequate content of water in the mixture, because low water content can caused the mix to be too stiff and the bubbles broke during mixing which resulted in an increased density, as it was shown by Nambiar et al. [16], [17]. In the same way, with high water content the segregation phenomenon can occur because the cement slurry is too thin to hold the bubbles, this also leads with an increase of the density [17].

A part from having an adequate content of water, it is also necessary to analyze the quality of the water. According to ACI 523.3R-93 [18], the water used for the foamed concrete creation should be potable water, since otherwise an organic reaction can have negative effects on the foamed mixture [19].

2.4.3. Aggregate

Coarse aggregate is not generally used in the production of foamed concrete mixtures as often as fine aggregates. The amount of fine aggregates used, ranges from 1500 to 1800 kg/m^3, is estimated once the volume of cement, water and air is defined in order to produce 1 m^3 of mixture. However, some references [20] have been found where amounts of aggregates are used from 550 to 1.550 kg/m^3 for the lightweight concrete production. However, and not really common, there are also references [21] where some coarse aggregate are used in an amount of 1/3 of the amount of fine aggregate.

Natural aggregate

Aggregates are the main component in a construction material mixture as the foamed concrete is. The type, classification and the form of the aggregates determine physical properties, in both fresh and hardened state, of the mixture, such as compressive strength.

Aggregates that have been used successfully are those that have the requirements of ASTM C33 (sand gravel, maximum particle size of 19 mm or less, sandy soils with more than 10% of material passing through the sieve N° 200, waste product from a quarry usually of 10 mm or less).

Excavated granular materials with lower properties than the concrete aggregates are a potential source to produce foamed concrete, and should be considered. In a research about obtaining foamed mortar from rejection crushing processes [12], the results showed that is possible to use fractions of aggregate surpluses, usually with high fines content in order to obtain foamed mortar.

Lightweight aggregate

This type of aggregates has a relative density lower than the normal aggregates (natural sand, gravel or crushed stone) [20].

There are different types of lightweight aggregates: structural lightweight aggregate, masonry lightweight aggregates and insulating aggregates, the difference between each of them is the value of the bulk density. The structural lightweight aggregates includes the aggregates prepared by expanding, pelletizing, or sintering products and aggregates prepared by processing natural materials such as pumice, scoria or tuff. The masonry aggregates includes the aggregates derived from a products of coal or coke combustion.

2.4.4. Air-entraining admixture

The foaming agents are responsible of the foamed concrete low density due to the creation of air bubbles (enclosed air-voids) in the cement paste. These foaming agents are originally synthetic, detergents, glue resins, resin soap, saponin, hydrolyzed protein or protein bases [22]. The most common are the last ones because gives as a result a stronger and more stable air bubbles network cells.

The addition of air in the mixture should be done when it has a viscous state and immediately after its production to ensure the stability [18]. The inclusion of this agent in the mixture has a considerable effect in both fresh and hardened state properties, as an example, an excessive quantity of foam result in a decrease of flowability due to the close structure the air voids creates. Following the regulations of ASTM C 869-91 and ASTM C 796-97 the stability of the foaming agent should be ensure [23]. The quality of the foam is important because is what gives stability to the foamed concrete, stability that affect the strength development and the stiffness of the material [17]. The compressive strength is usually greatly influenced by the water/cement ratio, although when talking about foamed concrete, the compressive strength is mostly affected by the foam content, and the type of foam agent used [24]. The inclusion of air, apart from affecting the compressive strength of the mixture, it also affect in the modulus of elasticity, but in a lower level [25].

2.4.5. Plasticizer admixture

Some additions are used to improve the properties of the mixture and to stabilize the foamed concrete [10]. Their use is limited between 0.45% - 5% of the addition volume. The plasticizers are used to increase the mobility of the fresh concrete, they are defined as water reducers, accelerating in this way the strength gain of the foamed concrete.

2.4.6. Other admixtures

Some researchers report that when foamed concrete was reinforced with fibers there has been an improvement of the mechanical properties [26]. However, later on it was reported that the fibers change the brittle behavior of the foamed concrete into a ductile elastic-plastic, and also, disturb the lightweight character of the material because of their heavy weight [27].

The fibers that can be used for the foamed concrete creation can be either natural or synthetic with volumetric fraction between 0.25% and 0.4% of the total volume [28].

2.5. Preparation techniques

There are different kind of techniques when preparing foamed concrete, the different techniques should control the quality and the mixing process of the foamed concrete [27]. The first method, is the mix-foaming method, where the foam agent is mixed along with all the basic constituents of the foamed concrete during the mixing process. It is necessary to acquire a foam that is steady and stable and that can create a strong skeleton of concrete all over the different voids [29], because until the cement sets, it has to resist the mortar pressure. The second method, is the pre-foaming method, and is based on preformed the foam independently from the base mix. Then, the foam is mixed with the base and could be produced by a wet or dry method.

2.6. Properties

The different properties of the material are classified depending on the state of the material, could be in the first minutes after their production, fresh state properties, or could be days after the production of the material, in this case its talked about hardened state properties. In this last case, is included the mechanical properties of the material. Each property is defined by their own characteristics, and the manufacturing process influences these single individualities.

2.6.1. Fresh state properties

The properties in fresh state of the foamed concrete are predominantly influenced by the value of the water to cement ratio (w/c), the quantity and type of air-entrained agent and the nature of the aggregates [30]. The characteristics of the mixture in fresh state includes the consistency, stability and rheology.

Workability

The presence of air-voids in the mixture due to the addition of foaming agent makes that foamed concrete present excellent performance in terms of workability [30]. For the characterization of the workability the regular test for normal concrete (slump test) can not be taken into account because of the material low density. In this case, the workability test should be evaluated visually, with an analysis of the mixture viscosity [31]. Not many researches have been done to analyze the minimum workability requirements of the mixture, because some studies have shown that high workability can come also with segregation problems. Is for that reason, that for the production of foamed concrete, the addition of plasticizers should not be spread in order to improve the workability, unless the w/c ratio has low value and the amount of addition is limited at 0.2% by weight of cement [32].

Even the regular test for measure the workability can not being applied in this type of material, there have been researchers that define as suitable the spreadability test. It is based in using a long open-ended cylinder (75x150 mm), and measured the spread in two perpendicular directions after the cylinder is raised vertically. An acceptable values for spreadability test were between 85 and 125 mm for regular mixtures (cement/sand), and if using fly ash in the mixture 115 and 140 mm.

Consistency

Consistency is affected by two mainly different factors related to the mix design constituents, first is the water content and second is the density of the coarse aggregates. The consistency is acceptable when the spreadability is limited more or less in 50% of the flowing time, where the flowing time is usually 20 seconds (time to place the mix into the molds and get a self-compaction of the material without any external energy) [7]. An increase in the w/c ratio and a reduction in the quantity of air entrained agent can increase the plastic density and reduce the consistency of the mixture [17]. For this, it is suggested to reduce w/c ratio to avoid the segregation phenomenon that could affect the workability and consistency of the mixture [33]. The density of the coarse aggregates could have adverse effects in the mixture consistency (the excessive volume of coarse aggregates would drop the bubbles of the mixture [34]), although, in this research no coarse aggregates are used, it is important to mention that the addition of fly ash in the mixture could settle this problem.

For all mentioned above, all the quantities of the mixture should be designed accurately enough to achieve a good consistency of the mixture, and suitable properties as self-compaction, cohesion and adhesion between the foaming agent and the binder [35].

Stability

The foamed concrete stability is defined as the adhesive behavior of the mixture, this includes the properties of consistency and cohesiveness [36]. Once a mixture is done and has a homogeneous aspect, meaning that is creamy, easily pourable and with fluid consistency, the mixture could be classified as stable which means that the material is free of bleeding and segregation [33]. Each property mention is related with the others, for example, an appropriate value of workability (45%) confirm a good stability of the foamed concrete mix design [15]. However, different factors can affect and decrease the stability of the mixture as the inclusion of mineral admixtures, or an excessive amount of foaming agent [37]. The addition of plasticizers, in small quantities, is recommended to avoid segregation or bleeding phenomenon.

The stability property can be analyzed by measuring the target density when the dosage was formulated and the real density once the mixture is done [17]. Another method to check the stability is to calculate the difference between the proposed w/c ratio when designing and the real value of the w/c ratio, the difference should be close to 2% [38].

Compatibility

The compatibility is a property that has become an important issue due to the appearance of incompatibility mixtures. This incompatibility mixtures had occur due to the lack of knowledge about the additions add in the manufacturing process of foamed concrete. The compatibility is a situation of strong interaction between the constituents of the mixture, more deeply, a good chemical collaboration between the admixtures and the foaming agent. When an incompatible mixture is designed, segregation occurs due to the lack of interaction [7].

The compatibility degree of the foamed concrete could be done by dividing the full height of a proposed cube before compacting over full height recorded minus the reduction in height due to retraction after compacting (for example at 3 days of curing age) [5]. In general, the dosage of plasticizers is recommended to be in a volume not exceeding 0.2% by weight of cement [39].

Flowability

Flowability is the property that makes a material suitable for use as backfill. Without the need for conventional placement and compaction equipment flowability allows that the material is self-levelling, flow within a hollow space, fill, and self-compacting. The placement of the material, when the hydrostatic pressure is important, should follow a process of successive layers, allowing the layer harden before applying the next one.

Flowability depends on the water/cement (w/c) ratio, when this ratio increases higher values are obtained [40]. Air entrained admixtures can also increase flowability up to 40% [41], as well as the use of fly ash [40]. In the same way that when a concrete in order to improve the flowability of the material a fluidizer admixture or a superplasticizer is added.

Density

The resulting material density depends on the materials used in the mixture. According to ACI 229R [3], the wet density of normal low-strength material is determined by ASTM D6023 [42], from a range of 1840-2320 kg/m^3. However, by using lightweight aggregates, such as silty sand or mixes with lightweight aggregate, lower unit weights can be achieved between 1360 and 1760 kg/m^3.

The inclusion of air reduces the density, then the density of the mixture is inversely proportional to the amount of air present [12] [43], but depend of the type of aggregate used [43] [44], being proportional the increase thereof. In cement-rich mixtures, increasing amounts of sand the density remains similar [12] because of in the mixture sand is not as remarkable as cement, in terms of density is concerned.

Settlement

The shrinkage is related with volume reduction of the mixtures as the water contained and trapped air through the consolidation of the mixture is removed. High ratios of water/cement (w/c) are given to allow the flowability of the mixture, but that provides an excess of water apart from that amount required to consolidate and moisturize, this excess is generally absorbed by the adjacent soil or removed through the surface as bleeding. The shrinkage typical value is between 3 and 6 mm for every 30 cm deep, this value is generally found in mixtures with high water content [11]. Mixtures containing appropriate water quantities have little or no shrinkage. The material settlement may be experienced during the first 2 to 4 hours after placement [45].

Setting time

According to ACI 229R [11], is the period of time that a mixture takes to acquires a state of hardening enough to support the weight of a person. Setting time is variable, and depends on the bleeding. When water excess come out of the mixture the contact and adhesion increases between the particles and the hardening process starts. It can be as short as an hour, but under normal conditions can take between 3 and 5 hours.
According to Dockter [44], the setting time has special interest to predict the feasibility and portability. The setting time can be defined in two different stages. The first stage which takes approximately 3 to 4 hours is when the mixture can support a person standing. The second stage, usually occurs in 1 or 2 days, and is when the mixture acquired stability to place products on it, such as cargo transport. Setting times are very important when the backfill is placed in layers.

There is a research [46] to determine if using stainless steel slag is feasible and its observed that increasing the water/matrix ratio (w/m) from 3.4 to 3.8 the setting time increase in 30%. The study also shows that the replacement of part of the conventional Portland cement for steel slag may increase setting time up to 62% according to the percentage replaced.

ASTM C403 [47] determines the setting time from its resistance to penetration.

Normal factors that have influence on the setting time are [11]:

- Cement: type and quantity
- Permeability and saturation degree of the soil around
- Relative humidity
- Mixture dosage
- Room temperature
- Moisture
- Backfill depth

Bleeding

Foamed concrete mixtures could present bleeding, if the dosage has water excess, with the addition of fly ash bleeding would be decrease and at the same time, flow properties improve the mixture. It could also be incorporated into the mixture high density aggregates or larger quantities of cement in order to reduce exudation [48].

In a research based on the constituent materials effects, the quantities in water demand and compressive strength of CLSM [48], bleeding values between 0 and 7.2 % were reported.

The standard test method to measure bleeding is determined by ASTM C232 [49].

Pump

Foamed concrete mixtures can be pumped, for this reason the dosage is critical. In the same way as for concrete pumping it is important to maintain a continuous flow through the pump line. If an interruption occurs the mixture could be segregate and this may cause plugging. The mixtures with high levels of air entrained can be pumped, but the bomber should be at low pumping pressures in order to not suffer considerable losses in air content and to not reduce the pumping capacity. Fly ash can help to the pumping acting as a micro aggregate to fill the gaps, cement can also be added for this purpose, although it should be careful to limit the strength thereof for not hinder the future excavation.

2.6.2. Hardened state properties

The characteristics of the mixture in hardened state defined the mechanical properties of the mixture, which describes the most important factors to measure the feasibility of the foamed concrete. These main properties are compressive, tensile and flexural strength and modulus of elasticity.

Compressive strength

The compressive strength development has a direct relationship with different parameters of the mixture as the density, w/c ratio, foaming agent, type of aggregate and curing method. There another parameters involved in the compressive strength value (cement/sand ratio, addition ingredients, etc.), although, the most influential parameters are the ones mentioned in first place [50].

Now, a deeply analysis of how each of the mentioned parameters condition the development of the compressive strength in foamed concrete mixtures.

- Density: the compressive strength of the mixtures has an exponential relationship with the density value, where a reduction in the density of the mixture affects adversely the compressive strength.
- Water/cement ratio: as it was mentioned in the fresh state properties, an appropriate amount of water enriches the consistency and stability of the mixture due to the fact that reduce the large size of the foam bubbles.
- Foam agent: in foamed concrete, the volume/density factor is one of the most important controllers of the compressive strength development due to the amount of air-voids [7], [51]. The excessive amount of this addition short the compressive strength of the mixture because the higher volume of foam agent increase the quantity of bubbles that leads in a reduction of the density [16], [17]. Some researchers found that the compressive strength at 28 days was 43 MPa and 0.6 MPa for densities values of 1800 kg/m^3 and 280 kg/m^3, respectively [52].
- Aggregates: the amount of sand respect to the quantity of the binder also conditions the compressive strength value. The use of fine sand with a regular granulometric distribution enrich the strength [17]. On the contrary, the use of coarse aggregate decline the strength due to the affection in the pore size distribution of the cement paste [16], [17]. It is usual to produce foamed concrete with sand/binder ratio between 1/1 and 4/1. The inclusion of additions as lime, clay or quarry dusts could increase the value of the strength [7].
- Curing method: the samples should be cured in a moist room with 100% of relative humidity three days before testing according to ASTM C 796 [23], then the samples should be oven-dried at 60 ºC for 72 hours. Some researchers have shown that in order to achieve a good value for compressive strength the samples should be cured in a normal moist air for one day, and then in a room which temperature increase 20 ºC/h [53]. However, when fly ash was added to the foamed concrete mixture, at least 50%, the curing temperature of 40 ºC is likely to be the most appropriate value for higher ultimate strength.
- Additions: some additions as silica fume or fly ash can make change the compressive strength development along the time. The substitution up to 65% of fly ash by cement result in no reduction of the ultimate strength [54], [55]. For the silica fume, the replacement should be lower, but due to the pozzolanic effect the strength increase more. The combination of both additions, silica fume and fly ash, could make increase the compressive strength up to 25% [56].

- Fibers: The addition of fibers in the foamed concrete mixture makes increase the compressive strength by obstructing the micro-cracks. However, not all the types of fibers are suitable for the foamed concrete production, the fibers must have high modulus of elasticity, sufficient size and length in order to develop the required strength through the foamed concrete paste [5]. If the fiber fraction range between 0.1% and 1%, the effect of restrain in shrinkage cracking became more significant [57].

Splitting tensile and flexural strengths

Splitting tensile strength is an indirect measure of the compressive strength of the mixture, meaning that all the factors that influence compressive strength also influence the tensile strength and vice versa [5]. As it was mentioned, the compressive strength of the foamed concrete is lower than the regular concrete, and because of the correlation of the different strength that had been commented, the tensile strength is also lower than that of normal concrete. Some researchers have reported that the splitting tensile and flexural strength are between a 15% and 35% of the total ultimate compressive strength [58]. The ratio of tensile strength to compressive strength of foamed concrete ranges between 0.2 and 0.4 which is higher compared to normal concrete that possesses a ratio of splitting tensile to compressive strengths between 0.08 and 0.11 [36].

One important factor on flexural strength is the water content, an excessive amount of this could reduce drastically these strength due to the decrease of the mix density [7].
The use of mineral admixtures or fibers give a good effect in the tensile strength capacity of the foamed concrete reducing the non-load cracks of the mixture at early ages. However, these fibers, just as it happens with the fibers of the compressive strength, should have enough length and size in order to make an appropriate development. The great advantage is that the material transform his behavior from brittle to ductile elastic-plastic, and these leads in an improvement of flexural strength, a durability development and enrich the post cracking behavior [26]. The tensile strength should be measured according to ASTM C496 [59].

Modulus of elasticity

The modulus of elasticity is related with the foamed concrete mix density, although, there are some investigators that associate this value with the type of aggregate [60]. The use of fine aggregates in higher proportions than the coarse aggregate increased the elastic modulus along time [57], it was noticed that the mixtures done with high content of coarse aggregate presented lower Young's modulus (E) compared with the same dosage but made with sand. The Young's modulus of foamed concrete is almost a 25% of the regular concrete, nonetheless, this low value of the modulus of elasticity could be compensate by the addition of different components, like fibers. The use of lightweight fly ash instead of fine sand gives higher results of the E value due to the interaction between the cement paste and the porous aggregates [34].

Excavability

The possibility to excavate the soil constitute by foamed concrete mixture in the future is an important consideration. Generally, a compressive strength of 0.3 MPa or less can be manually dug. Compressive strength between 0.7 and 1.4 MPa, mechanical equipment such as backhoes can be used. The mixtures that only consist of fine sand or fly ash as aggregate can be dig also with backhoes even if the compressive strength is 2.1 MPa [11].

When there is a possibility of a future excavation, the type and amount of cement is important. It has obtained a long-term acceptable behaviour with cement contents from 30 to 276 kg/m^3 [61]. In order to maintain low resistance, and limit the amount of cementitious material in the mixture, a foaming agent can be incorporated.

Given that foamed concrete mixtures typically continue gaining strength beyond the period of conventional test methods, it is suggested, especially for mixtures with high cementitious material that long-term tests can be conducted in order to estimate the potential of a subsequent excavation over the years.

Differential settlement

Traditional compacted fillings may suffer settlements even when compaction requirements have been made. By contrast, the foamed concrete mixtures do not undergo settlements after hardened [11].

According to ACI 229R [11], measurements taken in various works demonstrated the absence of contractions and settlements after hardened state. Moreover, in a project in Seattle Washington, in which 601 m^3 were used to fill a hole of 37 m depth, placement took 4 hours and differential settlement in the hardened state was 3 mm [62].

2.6.3. Physical properties

The physical properties of the foamed concrete includes density, porosity, shrinkage, and sorptivity. The sorptivity refers to the capillarity of the mixture.

Density

The density could be measured in both states of the mixture, fresh and hardened state. It is strongly necessary to control the value density in both states, each density value has its own purpose. The value of the density in fresh state is to control the total volume produce, while the value of the density in hardened state is a parameter that controls the mechanical properties of the mixture as it has been said in the previous sections of this research.

The density in fresh state could be measured by filling, with the already prepared mixture, and weighing a container with known volume. The density in dry state of the mixture should be calculated according to the regulation BS EN 12350: Part 6: 2000 [31]. Once both values have been obtained, an analysis of both densities should be done and is recommended that the difference between both values should be less than 100-120 kg/m^3 [55]. It is also recommended to make an analysis of the theoretical density and the fresh density.

There are some components of the mixture that affects in a greater extent than others. These main constituents are the foaming agent and the type of cementitious material used. It has been reported that the increase of foamed agent quantity affects the foamed concrete density lowering their value in fresh state [8]. On the other hand, the use of fly ash increased the dry density [17].

Porosity

Many factors affect the porosity of the mixture, like the main components of the mixture, the foaming agent and the type of curing process, for example. Mainly, the porosity depends on characteristics such as water absorption capacity, sorption and permeability [58]. There is also evidence that high values of the w/c ratio can caused porosity [63].
Foam agent is a great influencer in the foamed concrete mixture. Higher volume of additive result in an increase of the porosity since the foam structure is highly attributed with the shape, size, spacing between air-voids, size distribution, and volume of microspores [5]. However, a great quantity of additive can cause a bubble size expansion that leads in the accordingly compressive strength reduction [51], [60], [63], [64].

In order to reduce the porosity, additives (with pozzolanic behavior) [64], [65], mineral admixtures or fine materials can be used in order to distribute the air-voids of the mixture. For example, lime powder has the capability to reduce the porosity higher than that of fly ash due to its fine particles that could improve the compact composition of microstructure of hardened foamed concrete [56].
It is really important to analyse the porosity because it has a direct influence in another properties like compressive strength, tensile strength, flexural strength as well as durability due to the fact that the holes ease the transport of aggressive agents inside the mixture matrix.

Shrinkage

One of the main disadvantages of foamed concrete is the drying shrinkage that can occur during the first 20 days of the manufacturing process. Due to the type of aggregate, the higher amount of binder material and the water content the drying shrinkage of foamed concrete could be between 4 and 10 times higher than the shrinkage produce in normal concrete [66]. Some researchers have report that the amount of cement can produce adverse effects on the foamed concrete performance, it is suggested to reduce the water/binder ratio [7], [51]. However, this problem can be solved by the addition of fly ash or silica fume due to the lower heat of hydration [67], [68]. The drying shrinkage can be decrease with the addition of lightweight fly ash, silica fume, as it had been said before, but there are also different ways to decrease this phenomenon, like curing the samples in a room with a good moisture content [67], an increase of the foaming agent due to the expansion of the pore size. A decrease of up to 36% in drying shrinkage was observed when the foam volume increased to 50% of the total volume [51].

Sorptivity

Sorptivity is the physical property that measure the capillarity liquid absorption of the medium [66]. It is important to consider this property due to the fact that affect the durability of the mixture. The main factors affecting the water transmission (pores distribution) is the foaming agent, the type of aggregates, curing conditions and density. Some studies show that dosages with higher water absorption capacity were that mixtures free of mineral admixtures compared with the mixtures with replacement of cement by fly ash, because of its higher water-solids requirement for achieving a stable and workable mix [69]. The increasing amount of air volume in the mixtures could make decrease the sorptivity because the air entrained in the mixture does not contribute to the capillary suction that is the mechanism of transport [17].

ACI 213R [1] suggests that for lightweight materials the reasonable range of sorptivity degree should be between 4 and 8%.

2.6.4. Durability properties

The durability of a mixture is identified as the concrete capacity to repeal external agents that influence the internal structure and might cause depletion and reducing in this way the already stablished mechanical properties of the mixture. Two of the main durability properties are the permeability and the resistance to an aggressive environment.

Permeability

The permeability is the property that express the water flow under pressure in a saturated porous medium [70]. In foamed concrete mixtures, these water flow depends on the water absorption capacity (twice the normal concrete water absorption) as well as on vapor permeability [71]. However, there have been some studies where the effects on permeability property of aggregates and admixtures have been analyzed. Contrary to what might be believed the inclusion of air with a foaming agent does not increase significantly the permeability due to the fact that the produced bubbles are discrete and spherical and the formation of channels for the flow are scarce.

The inclusion of components with pozzolanic behavior as fly ash is influential in the permeability of the mixture [72]. An increase in the ash/cement ratio can also increase the water vapor permeability [73].

Resistance to aggressive environment

Due to the high porosity of the foamed concrete, the severity of the aggressive environments should be analyzed since this attack is based on the size, distribution and volume of the pores as well as the components of the mixture. These high porosity of the foamed concrete does not necessarily make it less resistant, on the contrary, the air voids of the cell structure act as defense [69]. Researchers recommend that when creating lightweight concrete it is necessary to consider many other factors apart from the cell distribution, like water adsorption rate, depth of primary penetration, etc.

One of the most aggressive agents to which foamed concrete is exposed is the sulfates attack, although, foamed concrete validate high resistance to sulfate and carbonation attacks [74]–[76]. The resistance of the lightweight concrete to carbonation was also evaluated, and it was observed that the addition of fly ash increase the resistance [54]. However, the increase in the foaming agent content reduce the carbonation resistance due to the declining of the value density because the carbonation occurs in a higher rate with low density values [60] [52]. On the other way, a decrease in the density value make the mixture more resistance to corrosion, for this, it is necessary to find an optimum balance of the density, because this low value protect the lightweight concrete in terms of corrosion [77].

2.6.5. Functional properties

The behavior of the foamed concrete are mainly defined by the functional properties, and actually, these type of specific characteristics is what make it look for an optimum mixture design of the material. For these, an overview about the most important functional properties are going to be defined below.

Thermal insulation and conductivity

The thermal conductivity is proportional to the density, when the density volume decrease the thermal conductivity decrease giving a higher value of thermal insulation. The thermal conductivity of a foamed concrete mixture depends, basically, on their components such the type of aggregate, the admixtures, the additive, etc. The replacement of natural aggregate by lightweight aggregate have shown positive results in the decreasing of the thermal conductivity levels [67], achieving until 1/6 of the standard thermal conductivity value for normal foamed concrete.

Regular values of foamed concrete thermal conductivity is 0.66 W/mK at 1600 kg/m^3 density, which is just a 41% of the normal concrete values (1.6 W/mK at 2200 kg/m^3). It has been said that for each 100 kg/m^3 of density reduction the thermal conductivity drop by 0.04 W/mK of the total insulation capacity. Its advantageous to use thicker layers of foamed concrete, to increase the total thermal insulation capacity of the structure [78].

Fire resistance

The fire resistance of a mixture depends on its mixture proportions and its components. Implicitly, the density of a mixture depends on is components and when the density decrease the fire resistance increase. Foamed concrete has shown the capability to resist fire inside certain acceptable values, although, the exposition to important temperatures cause high evaporation rates and an excessive shrinkage [79]. Different researchers [80] reported that foamed concrete with a density of 400 kg/m^3 showed a rate of resistance to fire which was three times lower than the one with dry density of 150 kg/m^3.

Acoustic insulation resistance

The acoustic insulation capacity of a mixture depends on the size, amount and distribution of the pores and, also, on the foaming agent [58], [60]. Due to the fact that foamed concrete are not a dense material, these lightweight concrete can reach 10 times higher absorption capacity of a sound absorption compared to normal concrete. Some researchers had attribute this higher acoustic insulation to the cell microstructure [58].

2.7. Costs

Some researchers [25] say that the production of foamed concrete costs about two thirds to three quarters of the ready-mixed concrete price. Lightweight concrete is generally more expensive per cubic meter than most conventional fillers. However, these costs depend on the materials used, the manufacturing process, transport and placement method. The mixing flexibility design has allowed some producers to develop foamed concrete with local materials, which are more economical. Moreover what makes it really economically attractive is the low cost of labor, short run times and minors inspection during placement.

2.8. Quality control

Quality control implemented to foamed concrete changes according to previous experiences, applications, materials used in the mixture and the desired level of quality. When the application is important and has not prior documents about the mixture used or when the mixture uniformity is doubtful, it would be appropriate carry out flowability and compressive strength tests. However, when preliminary tests have been carried to the mixture, control can be limited to a visual inspection of the entire work.

It is suggested that, in the relevant projects, a mixture design and preliminary tests of flowability, unit weight, strength, long load application, durability, permeability, etc.

Once the preliminary test program had been conducted, it should be necessary to define the test method that need to be performed in construction place.

The responsibility is to that person who does the technical specifications and to the mixture producer, to determine and implement an appropriate quality control for the mixture that need to me placed. Table 1 show some of the ASTM standards used to determine properties in fresh and hardened state of the foamed concrete.

Table 1. ASTM regulations

Regulation	Name	Property
ASTM C136	Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates	Particle size
ASTM C150	Standard Specification for Portland Cement	Binder quality
ASTM C232	Standard Test Methods for Bleeding of Concrete	Bleeding
ASTM C403	Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance	Setting time
ASTM C642	Standard Test Method for Density, Absorption, and Voids in Hardened Concrete	Density and Absorption
ASTM C796	Standard Test Method for Foaming Agents for Use in Producing Cellular Concrete Using Preformed Foam	Air entrained
ASTM C939	Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method)	Fluency
ASTM D559	Standard Test Method for Wetting and Drying Compacted Soil-Cement Mixtures	Durability
ASTM D1883	Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils	Strength
ASTM D4832	Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders	Strength
ASTM D5084	Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter	Permeability
ASTM D6024	Standard Test Method for Ball Drop on Controlled Low Strength Material (CLSM) to determine Suitability for Load Application	Setting time
ASTM D6103	Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)	Flowability
ASTM E1820	Standard Test Method for Measurement of Fracture Toughness	Fracture

CHAPTER III. MATERIALS AND EXPERIMENTAL PROCESS

In this chapter is described the properties of the materials that had been used to the development of the experimental process. In addition it is also described the manufacturing process to produce the foamed concrete, and detailed the testing procedure to analyses the behavior of the lightweight foamed concrete mixture in fresh and hardened state.

3.1. Materials

3.1.1. Cement

Cement Quikrete was used for the experimental process in the production of lightweight foamed concrete mixtures. It has 27.6 MPa average compressive strength blend of portland cement, sand, and gravel or stone [81]. This type of cement is made by heating limestone, iron, alumina, and silica [82].

Figure 5. Cement used for foamed concrete production

3.1.2. Water

The water used was ordinary tap water collected from the laboratory because meets all federal and state drinking water regulations. The city of Boulder have several high quality water sources that ensure population receive high quality drinking water.

Table 2. Water specifications [83]

pH	7.6
Nitrogen	$0.04\ \frac{mg}{l}$
Phosphorus	$2.9\ \frac{\mu g}{l}$
Aluminium	$11.7\ \frac{\mu g}{l}$
Calcium	$29.5\ \frac{mg}{l}$
Chloride	$6\ \frac{g}{l}$
Iron	$11\ \frac{\mu g}{l}$
Potassium	$1.1\ \frac{mg}{l}$
Sulfate	$16.1\ \frac{mg}{l}$
Zinc	$1.6\ \frac{\mu g}{l}$
Uranium	$0.03\ \frac{\mu g}{l}$

3.1.3. Natural aggregate

Natural aggregates were used in the manufacturing process of the foamed concrete mixtures. Locally available and provided by "*QUIKRETE*" Company, siliceous sand was used as natural aggregate for the different mixtures. Natural aggregate granulometric curve is show in Figure 8.

Table 3. Natural aggregate physical properties

Bulk Specific Gravity	2.58 kg/dm^3
Absorption	1.7 %
Humidity	0 %

Figure 6. Natural aggregate from siliceous nature

3.1.4. Lightweight aggregate

Lightweight aggregate used was sourced from a local treatment plant located in Boulder, Colorado: "*TRINITY Industries, Inc. Company*"

Figure 7. Lightweight structural fines

The chemical composition of the lightweight aggregates are relevant in order to analyze some important properties as thermal conductivity or resistance.

Table 4. Lightweight aggregate physical properties

Saturated Surface Dry	1.89 kg/dm^3
Bulk Specific Gravity	1.59 kg/dm^3
Apparent Specific Gravity	2.31 kg/dm^3
Absorption	19.85 %
Humidity	18.55 %

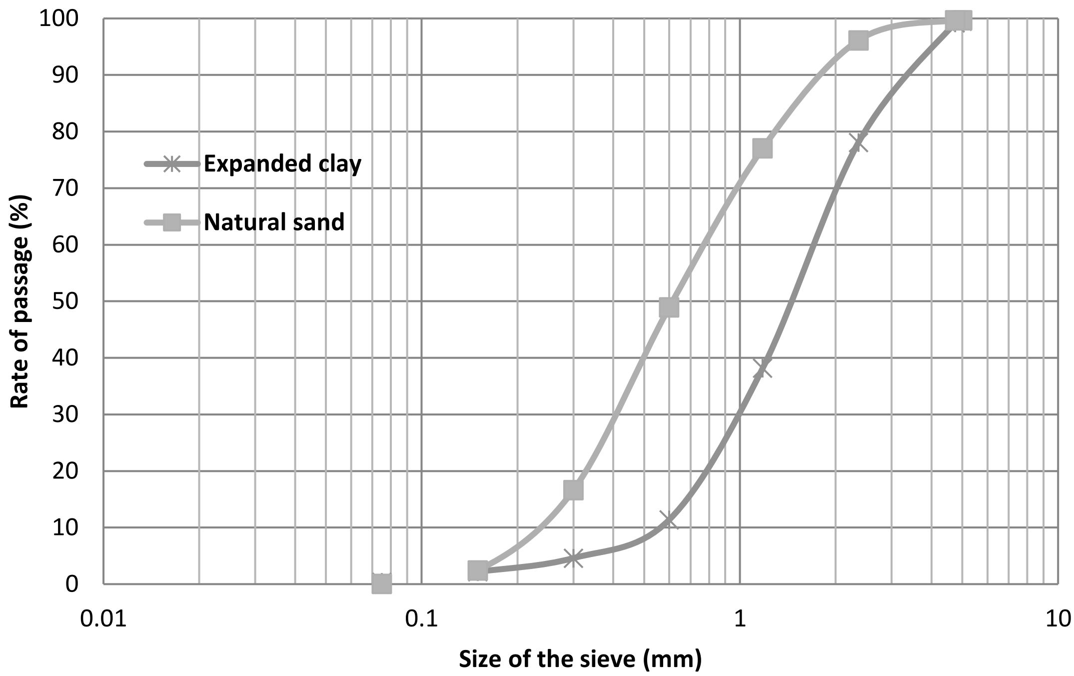


Figure 8. Granulometric curves (particle size distribution)

3.1.5. Air-entraining admixture

Figure 9. CMX admixture

CMX Foam Concentrate was used to entrain air in the foamed concrete mixtures. These foaming agent is used for the production of cellular concrete, and is a synthetic based foam concentrate. These type of additive offer longer shelf life, have no obnoxious odor, and perform well under a variety of conditions. It is compliant with the specifications of ASTM C869 [84].

3.1.6. Superplasticizer admixture

Figure 10. Superplasticizer admixture

Sika Viscocrete 2100 is a superplasticizer that is also known as a high range water reducer. These type of additives provide excellent plasticity while maintaining slump for up to 90 minutes. The use of this type of admixtures is based in the given benefits as higher ultimate strengths, reduced water/cement ratio that produce more durable and dense concrete with reduced permeability [85].

3.2. Manufacturing process

The manufacturing process of all lightweight foamed concrete were made in the laboratory located at the Department of Civil, Architecture and Environmental Engineering at the Colorado University Boulder (CU Boulder).

3.2.1. Mixing receptacle

The receptacle shall be a suitable cylindrical container with sufficient capacity to allow easy sampling and remixing of the foamed concrete mixtures. The container must conform the requirements of being free of corrosion, coatings or lubricants.

In the manufacturing process of foamed concrete have been used two different types of receptacles. The type of container used was chosen depending on the part of the manufacturing process of this research.

For stage 1 and stage 2 was used the mixers show in Figure 11 (left) with the object of produce a limited quantity of 2 litres for each mixture. For stage 3, the regular mixer used for produce concrete (Figure 11, right), was used for produce 20 litres of lightweight foamed concrete.

Figure 11. 2 and 20 litres mixer

3.2.2. Concrete mixing and forming procedures

Weighting

First is necessary to grade the aggregates that are going to be used in the manufacturing process. For foamed concrete just fine aggregates (sand) are going to be used. In second place, it is necessary to weight the total amount of water and cement according to the proposed dosage.

Mixing

1. First, it is necessary to wet the mixer with water, pouring out the water.
2. Then, add the fine aggregates in the mixer with the total amount of cement, then mix for 1 minute. Then stop the mixer, and add the water to the mixer.

3. Start the mixer and mix the concrete for 3 minutes, follow by 3 minutes rest, follow by a final 2 minutes of final mixing. During the rest period is necessary to cover the mixer to prevent the evaporation.
4. Finally, deposit the concrete in a dampened wheelbarrow, and clean the mixer.

Placing in forms

To eliminate segregation, a re-mixed of the concrete by shovel or trowel until it appears to be uniform. Then a small cover of oil in the test samples walls will ease the demoulding procedure. Fill the cylinder with foamed concrete in two different layers equally, in this case it is no necessary any extra compaction energy than the own mixture settlement. Screed and excess concrete from the top to form a flat surface, wipe off concrete from outside walls and cap. Label and place the concrete specimens in the curing room.

Clean up

Excess concrete: once all the test specimens are filled, the excess concrete should be spread out on the tin sheets so that it can harden and be thrown away. It is necessary to clean all the tools used, the mixer, and the wheelbarrow need to be rinsed with water. It is necessary to try to get as much of the concrete out of the mixer as possible.

Curing

The foamed concrete will harden in the first 24-48 hours. It will gain most of its strength in the first 28 days. During this time, the specimens will be cover with film in a controlled environment room that maintains a constant temperature with no significant changes.

The purpose of cover the surface with film (a non-absorbent material) is to avoid the moisture loss of the mixture. In this case, the film does not interfere with the sample surface because the curing process is made once the sample has achieved sufficient hardening [86].

Figure 12. Curing process with film

Mold removal

During 24-48 hours after the mix, it is necessary to remove the molds from the specimens.

Sulfur capping

Prior to performing compressive strength tests on cylindrical foamed concrete specimens, it is important to understand that proper end preparation ensures that the ends of concrete test cylinders or cores have smooth, parallel bearing surfaces perpendicular to the applied axial load to assure uniform distribution of forces during testing. Capping of concrete cylinders and drilled concrete cores with sulfur mortar prepares specimens for compressive strength testing. ASTM

C617 is a method using molten sulfur mortar to form bonded caps. Specific criteria should comply with ASTM C39 specifications for planeness and perpendicularity of specimens [87].

Figure 13. Capping of the foamed concrete mixtures

3.2.3. Natural aggregate

In stage 1, was used just natural aggregate in order to find a control dosage that could be used as a pattern. In all the mixtures made with just natural aggregate was used the same sequence. First of all, the natural aggregates and cement were introduced in the mixer and shake for one minute, then water was added. After one minute of mixing with the mixer working, the air-entraining admixture dissolved in water (the amount which would be absorbed by aggregates) was also added to the mixture. Then, after 1 minute the mixer was stopped for 30 s in order to clean the mixer walls because its highly probable that the natural aggregate still remained untouched by the mixer blades, and finally started again for a further 3 minutes of mixing.

3.2.4. Lightweight aggregate

In stage 2, natural aggregates was replaced by lightweight aggregate in different quantities. The manufacturing process was the same developed in stage 1. First, the cement, natural and lightweight aggregates were introduced all together in the mixer. After one minute of mixing all the components were combined. Then the water was added (one more minute of mixing), continuedly, the foaming agent was added dissolved in the amount of water absorbed by the aggregates. After one more minute of mixing, the walls of the mixer were cleaned and finally, three more minutes of mixing to end up the process.

3.3. Experimental process

In this section is described the three experimental stages carried out that are part of the manufacturing process of the lightweight foamed concrete production.

3.3.1. Stage 1

Having analyzed different types of dosages of foamed concrete that had been used in the literature review with cement, water, natural aggregate and admixture (a foaming agent), a dosage has been set as a starting point to produce the foamed concrete. Then the manufacturing process starts on the laboratory with natural aggregate with the target of provide an optimum mixture that achieves the specific requirements defined by the different regulations in fresh and hardened state.

The analysis criteria used to find the correct proportions were, in fresh state, the density and the air entrained following by the compressive strength in hardened state at 7 and 28 days and the density, porosity and absorption at 28 days of every mixture.

The processes to improve the material when the previous properties mentioned had been already analyzed were based on the modification of the quantities of one of the constituents of the mixture in order to find the adequate interval of density, air entrained and compressive strength. In this stage, all the dosages were made with just natural aggregate.

3.3.2. Stage 2
Mix proportions of foamed concrete employing lightweight aggregate

Once the correct mixtures proportion have been defined in stage 1 with just natural aggregate, the manufacturing process of foamed concrete with lightweight aggregates started. The percentage substitution of the natural aggregate by recycled aggregate was starting for a quantity of 10%, 20%, continuously with 50% and finally with the 100%.

In order to find the optimum mix proportions mixing natural aggregate with lightweight aggregate the criteria was the same used in stage 1 (density, porosity and compressive strength) producing 2 litres of each mixture.

The target in stage 2 was to substitute the maximum natural aggregate by lightweight aggregate as possible.

3.3.3. Stage 3
Optimum dosage for beams production

Once an optimum mix proportion have been defined in stage 2, these optimal mixtures are going to be done and prepare for fracture test. The beam specimens of foamed concrete are symmetrically notched, and will be loaded near the notches by concentrated forces that produce a concentrated shear force zone, until failure.

The interesting part of this analysis is that cracks do not propagate from the notches in the direction normal to the maximum principal stress but in a direction in which shear stresses dominate. Thus, the failure is due essentially to shear fracture. The results are of interest for certain types of structures subjected to blast, impact, earthquake, and concentrated loads.

3.4. Testing procedure

Fresh and hardened properties were determined in all the different mixtures. The properties in fresh state (unit weight and air content [42]) were tested immediately after mixing.

According to the hardened properties, the test elements were demold and cured with film protection after 24-48 h after their production. They were kept in a controlled environment room until the test date was 7 or 28 days.

Cylindrical test specimens of 2x4 inches were tested to determine the different properties to analyse. Compressive strength and density, absorption and porosity tests were done after 28 days.

3.4.1. Test specimens

Due to the low strength that the dosages are, the mixtures need to be molded for at least 48 hours. It has been done a large amount of cylinders samples and they are going to be reused, in order to maintain the manufacturing process in continuous movement.

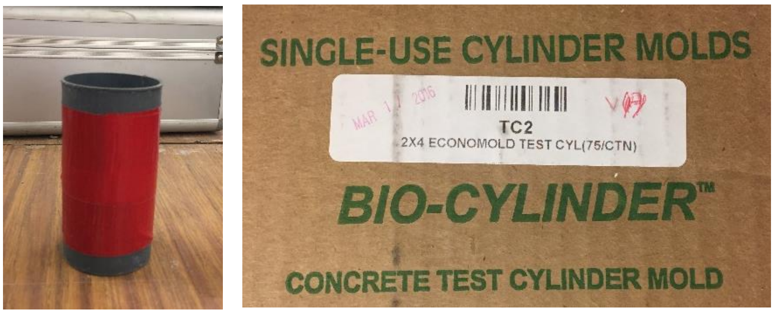


Figure 14. Test specimens

3.4.2. Test method in fresh state

This test method provides a procedure to determine the status of a freshly foamed concrete mixture. They are also intended to assist the quality control purposes and when specified to determine compliance for some specific characteristics.

Every single method is one of a series of quality control tests that can be performed on foamed concrete during construction to monitor compliance with specification requirements.

Test method for Density and Air content

According to ASTM D 6023-07 [42] the standard test method for density (unit weight) explains the determination of the density of fresh mixtures.

The density of the foamed concrete mixture is determined by filling a recipient with mixture, determining the mass, and calculating the volume of the container. The density is then calculated by dividing the mass by the volume.
A cylindrical container made of PVC is used to determine the density. It shall be watertight and sufficiently rigid to retain its form and calibrated volume under rough usage.

Procedure

1. Place the container on a level, rigid, horizontal surface free from vibration and other disturbances.
2. Thoroughly mix the sample of foamed concrete in the sampling and mixing receptacle to ensure uniformity.
3. With the filling apparatus, scoop through the center portion of the sample and pour the foamed concrete into the measure. Repeat until the container is full.
4. On completion of filling, the measure shall not contain a substantial excess or deficiency of foamed concrete mixture.
5. After filling, strike-off the top surface of the foamed concrete and finish it smoothly with the flat strike-off plate using great care to leave the measure just level full.
6. After strike-off, clean all excess foamed concrete from the exterior of the measure and determine the gross mass of the mixture.

3.4.3. Test method in hardened state

The detailed testing procedure to analyses the behaviour of lightweight foamed concrete mixtures in hardened state are described below.

Test Method for Compressive Strength

According to ASTM D 4832-10 [88] the standard test method for preparation and testing test cylinders covers the procedure for the compressive strength determination.

Compressive strength testing is performed to assist in the design of the mix and to serve as a quality control technique during construction. Mix design is typically based on 28-day strengths and construction control test performed 7 days after placement. The cylinders are prepared by pouring a representative sample into molds, then depending on the strength development, either curing the cylinders then removing them from the molds, and preparing the cylinders for compression testing.

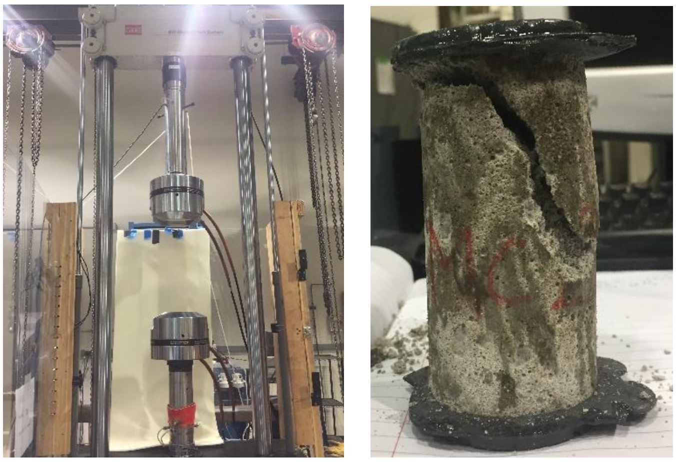


Figure 15. MTS Compressive strength machine (left) and test sample of compressive breaking load (right)

Procedure

1. Place the lower bearing block, with its hardened face up, on the table of testing machine directly under the spherically seated (upper) bearing block. Wipe clean the bearing faces of the upper and lower bearing blocks and of the test cylinder, and place the test cylinder on the lower bearing block. As the spherically seated block is brought to bear on the top of the cylinder, rotate its movable portion gently by hand so that uniform seating is obtained.
2. Apply the load continuously and without shock. Apply the load at a constant rate such that the cylinder will fail in not less than 2 minutes. Make no adjustment in the controls of testing machine while a specimen is yielding rapidly immediately before failure.
3. Apply the load until the cylinder fails, and record the maximum load, to either two or three significant digits, carried by the cylinder during the test. For about one out of every ten cylinders, continue the loading until the cylinder breaks enough to examine the appearance of the interior of the specimen.

Test Method for Density, Absorption, and Voids in Hardened Concrete

According to ASTM C 642-06 [89] the standard test method covers the determinations of density, percent absorption, and percent voids in hardened concrete. The samples shall consist of several individual portions of foamed concrete mixture, each to be tested separately and shall be free from observable cracks, fissures, or shattered edges.

Procedure

1. Determine the mass of the portions, and dry in an oven at a temperature of 100 to 110°C for not less than 24 hours. After removing each specimen from the oven, allow it to cool in dry air to a temperature of 20 to 25 °C and determine the mass. If the specimen was comparatively dry when its mass was first determined, and the second mass closely agrees with the first, consider it dry. If the specimen was wet when its mass was first determined, place it in the oven for a second drying treatment of 24 hours and again determine the mass. If the third value checks the second, consider the specimen dry. In case of any doubt, redry the specimen for 24 hours periods until check values of mass are obtained. If the difference between values obtained from two successive values of mass exceeds 0.5% of the lesser value, return the specimens to the oven for an additional 24 h drying period, and repeat the procedure until the difference between any two successive values is less than 0.5% of the lowest value obtained.

Figure 16. Oven-dried samples

2. Immerse the specimen, after final drying, cooling, and determination of mass, in water at approximately 21 °C for not less than 48 h and until two successive values of mass of the surface-dried sample at intervals of 24 h show an increase in mass of less than 0.5% of the larger value. Surface-dry the specimen by removing surface moisture with a towel, and determine the mass.

Figure 17. Immerse samples

3. Place the specimen in a suitable receptacle, covered with tap water, and boil for 5 h. Allow it to cool by natural loss of heat for not less than 14 h to a final temperature of 20 to 25°C. Remove the surface moisture with a towel and determine the mass of the specimen.
4. Suspend the specimen, after immersion and boiling, by a wire and determine the apparent mass in water.

Test Method for Measurement of Fracture Toughness

According to ASTM D E 1820-01 the standard test method that covers the procedure for determination of fracture toughness [90]. Toughness can be measured in the R-curve format or as a point value. The fracture toughness determined in accordance with this test method is for the opening mode (Mode I) of loading.

The objective of this test method is to load a fatigue a pre-cracked test specimen to induce either or both of the following responses (1) unstable crack extension, including significant pop-in, referred to as “fracture instability” in this test method; (2) stable crack extension, referred to as “stable tearing” in this test method. Fracture instability results in a single point-value of fracture toughness determined at the point of instability. Stable tearing results in a continuous fracture toughness versus crack-extension relationship (R-curve) from which significant point-values may be determined. Stable tearing interrupted by fracture instability results in an R-curve up to the point of instability [90].

Procedure

The overall objective of the test method is to develop a load-displacement record that can be used to evaluate *K, J,* or CTOD. Two procedures can be used:

1. A basic procedure directed toward evaluation of a single *K, J,* or CTOD value without the use of crack extension measurement equipment.

The basic procedure utilizes a load versus displacement plot and is directed toward obtaining a single fracture toughness value such as K_{1c}, J_c, or d_c. Optical crack measurements are utilized to obtain both the initial and final physical crack sizes in this procedure. Multiple specimens can be used to evaluate *J* at the initiation of ductile cracking, J_{1c}, or d_{1c}.

2. A procedure directed toward evaluation of a complete fracture toughness resistance curve using crack extension measurement equipment. This also includes the evaluation of single-point toughness values.

The resistance curve procedure utilizes an elastic unloading procedure or equivalent procedure to obtain a *J*- or CTOD-based resistance curve from a single specimen. Crack length is measured from compliance in this procedure and verified by posttest optical crack length measurements.

CHAPTER IV. MIX PROPORTION DETERMINATION

In this chapter the dosages did to make foamed concrete are described and is given the obtained results in fresh and hardened state for each of the two experimental stages that had been done.

4.1.Stage 1

Various mixing proportions with cement, water, a foaming agent and natural aggregate were produced in order to define the optimum dosage that met the specific requirements in both fresh and hardened state. These requirements were air content (35-42%) [5], [35], unit weight and compressive strength. For unit weight and compressive strength there were not specifics values to achieve, because the aim of this research was to find an optimum balance between both parameters in order to have a good insulation and structural material.

The process used to determine the mix proportion was the following: first the water/cement ratio and the amount of cement to be used for production of 1 m^3 of foamed concrete were defined and the amount of water was calculated. Second, assuming that there was 30% of air content, the volume of aggregates was determined. In each mixture, the air volume and the density in fresh state were measured in order to verify the production of the estimated volume material.

Dried natural sand was used and during mixing the water absorbed by the aggregates was added. It was estimated that the effective absorption capacity of the natural sand was 65% of the total absorption capacity.

For the productions of foamed concrete a cement/aggregate ratio of 1/5 approximately was set, 250 kg of cement and water/cement ratio value of 0.7 were used in all mixtures. Different amounts of additive (foaming agent) were applied (see Table 5).

Table 5 shows all the dosages that have been used in the laboratory in order to obtain a control mixture. All the dosages have been designed to have a 30% of air in the 1 m^3 of material.

The designation of the mixtures is "*MC X*" where MC refers to conventional mortar because the use of conventional aggregates (natural sand), and X makes reference to the type of the proportions that were studied

Table 5. Foamed concrete dosages for MC (m3)

Description	w/c	Cement (kg)	Water (kg)	Natural sand (kg)	Additive (l)
MC 1	0.7	250	175	1148.33	1100
MC 2	0.7	250	175	1148.33	1000
MC 3	0.7	250	175	1148.33	1100
MC 4	0.7	250	175	1148.33	900
MC 5	0.7	250	175	1148.33	750
MC 6	0.7	250	175	1148.33	600
MC 7	0.7	250	175	1148.33	400
MC 8.5	0.7	250	175	1148.33	250

The different mixtures described above are foamed concrete mixtures with a big quantity of air entrained, more specifically, all the mixtures have been designed to have a 30% of air respect to the total volume.

During the whole manufacturing process, the goal was to achieve high porosity, a value between 35% and 42%. Due to that in all the entire process the only variable of the mixtures were the quantity of admixture added.

Fresh state properties

In all the mixtures it was supposed that the natural aggregate absorbed 65% of his own capacity (1.7%), that is the total absorption capacity of the natural aggregate when half an hour were past. It is also possible to suppose that the natural aggregate absorbed his own capacity once 10 minutes were past, that correspond to a 30%. The decision of choosing one value or another raised on the experimental process and the visualisation of the aggregates once the total amount of water was added in the mixer.

Table 6. Fresh state properties of MC

Description	Density (kg/dm^3)	Porosity (%)
MC 1	1.79	10.14
MC 2	1.19	62.86
MC 3	1.28	54.28
MC 4	1.40	43.52
MC 5	1.46	38.33
MC 6	1.45	39.28
MC 7	1.44	40.34
MC 8.5	1.64	26.91

As it is possible to see in Table 6, the mixture with less porosity is the MC 1, although, is the mixture with more amount of additive added (Table 5), this is because the admixture added, just in this case was a plasticizer instead of a foaming agent.

The next mixture produce was MC 2 and it was used an amount of 1000 l (per m^3) of foaming agent, that quantity produce a mixture with high porosity (62.86%). From then, the procedure was to decrease the amount of admixture used until a mixture with porosity between 35% and 42%. The suitable mixtures in this stage were MC 5, MC 6 and MC 7.

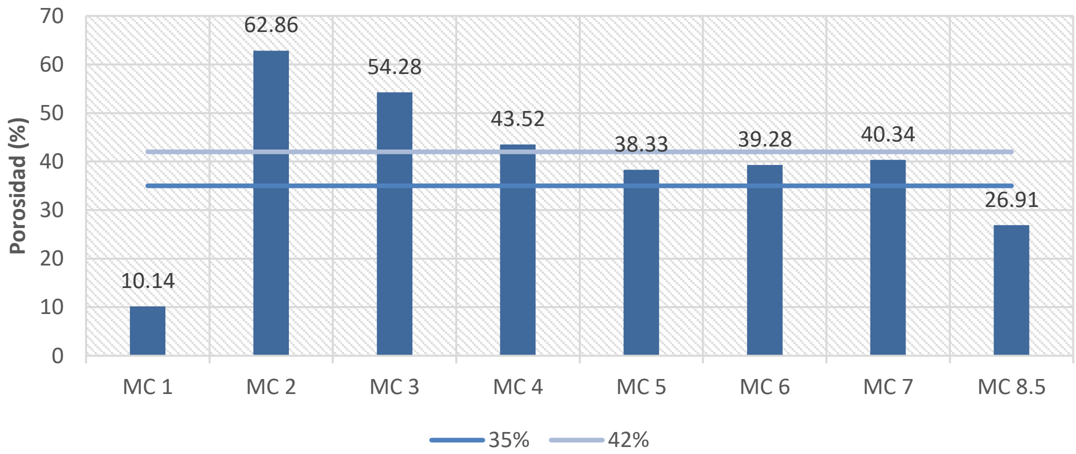


Figure 18. Porosity for conventional mortar (MC)

In Figure 19 it is shown the porosity of all the different mixtures related with the density value. As it is possible to see, low values of porosity indicates high densities values, an the other way around, mixtures with higher porosity ranges has the lower density values. In this first stage, and for conventional foamed concrete made of just natural aggregate the suitable mixtures were MC 5, MC 6 and MC 7 and this mixtures has an approximate density value of 1.45 kg/dm^3.

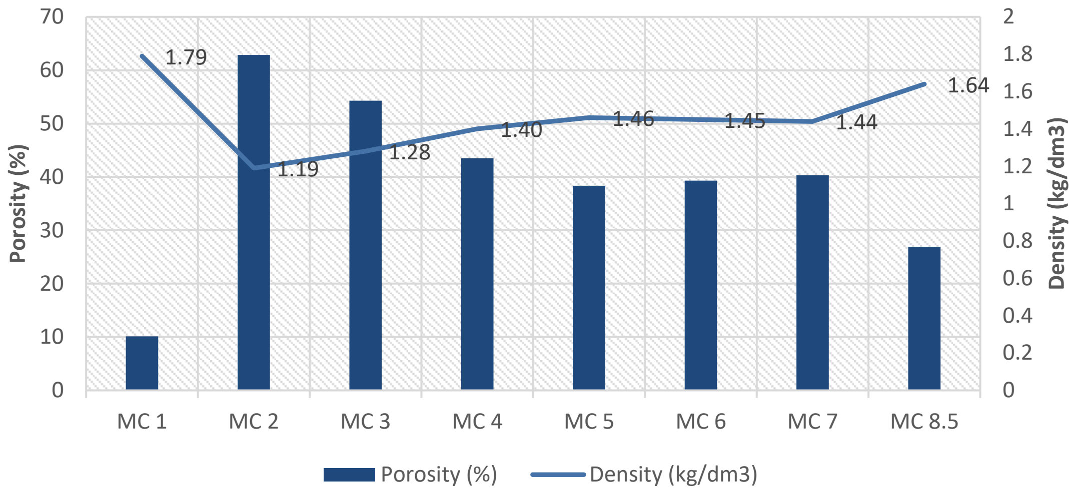


Figure 19. Porosity and density for conventional mortar (MC)

The suitable mixtures were that ones made with approximately 500-600 l (per m^3) of foaming admixture reaching density values of 1.5 kg/dm^3.

Hardened state properties

Compressive Strength

In Table 7 is shown the compressive strength values of the different mixtures that has been done for conventional foamed concrete. The highest value was MC 1 with 12.33 MPa, but as it has been mentioned before, that mixture has a very low porosity (10.14%) due to the admixture used, that were a superplasticizer instead of a foaming agent.

Table 7. Compressive strength for MC mixtures

Description	**Compressive strength (MPa)**	
	7 days	**28 days**
MC 1	9.82	12.33
MC 2	0.43	1.22
MC 3	1.37	1.89
MC 4	1.59	1.24
MC 5	2.34	2.54
MC 6	1.87	1.69
MC 7	1.69	1.66
MC 8.5	5.88	6.58

If the first mixture is erased because of the additive used, the next mixture with highest compressive strength, and that has suitable fresh properties, is MC 5, which was one of the adequate mixtures when fresh properties were analysed. In previous sections it was also defined that the suitable mixtures were MC 5, MC 6 and MC 7 which has a porosity value of 38.33%, 39.28% and 40.34% respectively. This values of porosity leads into compressive strength values at 28 days of 2.54, 1.69 and 1.66 MPa, respectively. What is possible to analyze is that higher porosity values leads into lower compressive strength mixtures.

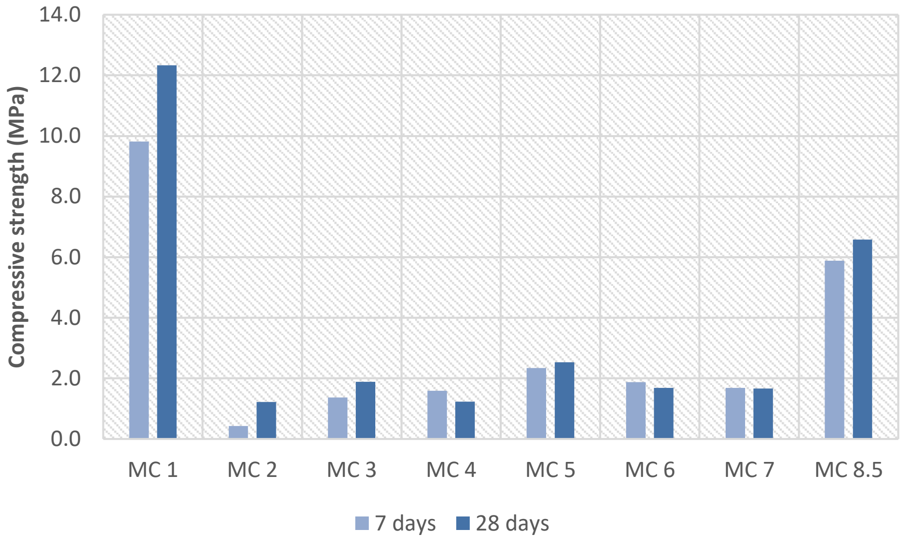


Figure 20. Compressive strength for MC mixtures

However, as long as it is necessary to find an structural material, it is necessary to find a material with higher strength than 2.1 MPa but less than 8 MPa. Mixtures with less strength than 2.1 MPa would be a good material for future excavations, but cannot be consider as suitable dosage for structural materials.

For all the things mentioned above, mixture MC 5 is the best natural foamed concrete mixture, which has an amount of admixture of 750 l (m3), a porosity of 38.33%, a density value of 1.46 kg/dm3 and this properties leads into a 2.54 MPa of compressive strength at 28 days.

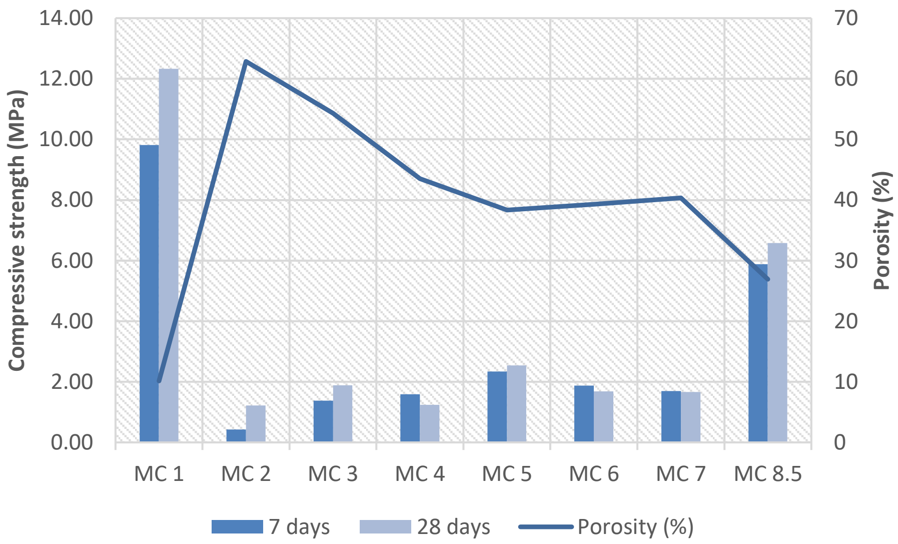


Figure 21. Compressive strength related to porosity for conventional mixtures (MC)

Once one suitable mixture has been defined in this stage (MC 5), in the next stage the natural sand replacement by lightweight aggregate are going to be done based on that suitable dosage.

Density, Porosity and Absorption

The dry densities of foamed concrete mixtures made with just natural aggregate are in a range between 1.15 and 1.5 kg/dm^3. The mixture MC 1 is exclude from the analysis because the additive used was a superplasticizer instead of a foaming agent.

The quantity of additive added in the mixture is of the utmost importance because influence inversely proportional the dry density values. The fact of have boiled the specimens make an increase in the bulk density, although, all the values obtain after boiling could be consider as more real values.

Table 8. Densities, porosity and absorption for MC mixtures

	Densities (kg/dm3)				Porosity	Absorption	
	Bulk						
	Dry	Saturated	After boiling	Apparent		Saturated	After boiling
MC 1	1.82	1.99	1.98	2.17	16.45%	9.39%	9.06%
MC 2	1.15	1.35	1.59	2.06	44.21%	17.51%	38.40%
MC 3	1.32	1.46	1.64	1.95	32.27%	10.96%	24.48%
MC 4	1.30	1.44	1.66	2.04	35.86%	10.53%	27.49%
MC 5	1.35	1.49	1.60	1.81	24.55%	9.90%	18.12%
MC 6	1.37	1.51	1.61	1.80	23.89%	10.30%	17.49%
MC 7	1.21	1.34	1.43	1.56	21.95%	10.66%	18.08%
MC 8.5	1.50	1.63	1.59	1.65	9.21%	8.40%	6.13%

Moreover, the porosity ranged from 9.21% to 44.21%, and the absorption from 6.13% to 38.4%. In this case, it is also possible to see a clear, and proportional, influence between the amount of additive added and the porosity/absorption degree.

4.2. Stage 2

Different mix proportions of foamed concrete using different percentages of lightweight aggregates were produced and tested in this stage. The initial mix proportions were based on the optimal dosage obtained in stage 1 (MC 5), in order to analyze the influence of the lightweight aggregate on the different properties of the material. All the dosages have been defined in order to obtain a 30% of air for each 1 m^3 of material.

4.2.1. Mix proportions of foamed concrete employing lightweight aggregate

The mixtures of foamed concrete, made with 10%, 20%, 50% and 100% of lightweight aggregate on substitution (by volume) of natural aggregates were produced. The analysis of mix proportions was carried out according also with the requirements defined in the previous stage.

The designation of the mixtures is *"MC AL X Y",* MC for conventional mortar, AL for the use of lightweight aggregate, and where X makes reference to the percentage of lightweight aggregate that was substitute and Y the type of proportions that were studied.

Taking into account the same physical state of the natural sand as in the previous stage, natural sand was in dry state and it was supposed that has a total absorption capacity of 65%. However, lightweight aggregates had an absorption capacity of 19.85% while the humidity was 18.55%. That means that the effective absorption capacity of the lightweight aggregates was 1.3%.

Table 9, Table 10, Table 11 and Table 12 shows the different mix proportions of the foamed concrete produced with different percentages replacement of lightweight aggregate.

The starting point was 10% of natural sand replacement by lightweight sand, and the dosage defined for produce 1 m^3 of material with 30% of air is shown in Table 9.

Table 9. Lightweight foamed concrete dosages of 10% replacement (m3)

Description	w/c	Cement (kg)	Water (kg)	Natural sand (kg)	Lightweight sand (kg)	Additive (l)
MC AL 10 1	0.7	250	175	1033.50	26.50	300

Table 10 shows the different mix proportions of foamed concrete produced with 20% replacement of lightweight aggregate for 1m^3 of material with 30% of air. Once the properties of the lightweight aggregate were analyzed it was decided to classify the lightweight aggregate as a structural material because of the high density value (1.6 kg/dm^3) compared with the other types of lightweight aggregates.

Table 10. Lightweight foamed concrete dosages of 20% replacement (m3)

Description	w/c	Cement (kg)	Water (kg)	Natural sand (kg)	Lightweight sand (kg)	Additive (l)
MC AL 20 4	0.7	250	175	918.67	140.00	500
MC AL 20 5	0.7	250	175	918.67	140.00	800
MC AL 20 6	0.7	250	175	918.67	140.00	1500
MC AL 20 7	0.7	250	175	918.67	140.00	3000

Table 11 shows the mix proportions of foamed concrete produced with 50% replacement of lightweight aggregate for 1m^3 of material with 30% of air. In all the dosages produced, the w/c ratio was maintained constant. However, in some point of the experimental process it was necessary to increase the amount of cement and water (MC AL 50 4), but maintaining always the w/c cement ratio at 0.7.

Table 11. Lightweight foamed concrete dosages of 50% replacement (m3)

Description	w/c	Cement (kg)	Water (kg)	Natural sand (kg)	Lightweight sand (kg)	Additive (l)
MC AL 50 1	0.7	250	175	574.17	350.02	5000
MC AL 50 2	0.7	250	175	574.17	350.02	7000
MC AL 50 3	0.7	250	175	574.17	350.02	10000
MC AL 50 4	0.7	300	210	507.00	309.08	7000
MC AL 50 5	0.7	250	175	574.17	350.02	7000

Table 12 shows the mix proportions of foamed concrete produced with 100% of lightweight aggregate for 1m^3 of material with 30% of air.

Table 12. Lightweight foamed concrete dosages of 100% replacement (m3)

Description	w/c	Cement (kg)	Water (kg)	Natural sand (kg)	Lightweight sand (kg)	Additive (l)
MC AL 100 1	0.7	250	175	0.00	700.04	8000

Fresh state properties

For the analysis of the fresh state properties it was supposed that the total absorption capacity of the natural aggregates was 65% of their absorption capacity (1.7%), and for the lightweight aggregates it was supposed that the total absorption capacity was that absorption when 30 minutes were past, 70% of 1.25% taking into account the humidity of the aggregates.

A. Mixtures with 10 % of lightweight aggregate

The first mixture was with 10% of aggregate replacement. There are difficulties when analysing the influence due to the MC AL 10 1 mixture behaves quite similar to the suitable mixture MC 5 defined in the previous stage.

Table 13. Fresh state properties of 10% replacement

Description	Density (kg/dm^3)	Porosity (%)
MC AL 10 1	1.65	20.96

The mixture with 10% of replacement and with an amount of foaming agent of 300 l/m^3 does not show a good performance of the lightweight aggregate because the porosity value obtained is far from the designed value (20.96% < 30%).

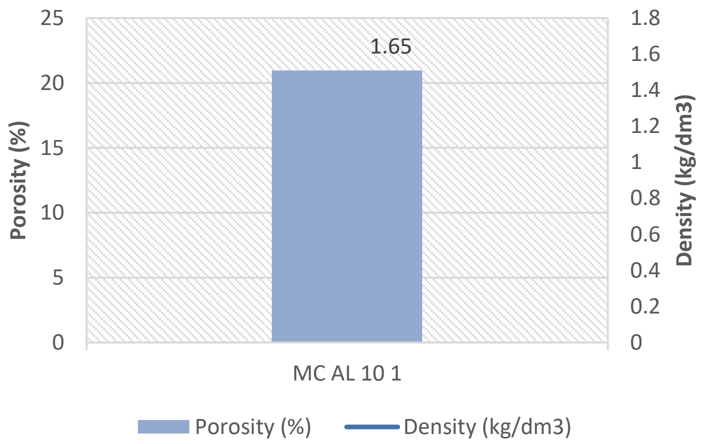


Figure 22. Porosity and density for 10% of lightweight aggregate (MC AL 10)

Analysing the previous mixtures made with just natural aggregate, the first samples shown low influence of the lightweight aggregate and the porosity is not what it was previously designed (20.96% < 30%), for this it was decided to increase the replacement percentage until 20%.

B. Mixtures with 20 % of lightweight aggregate

As it has been mentioned in past sections, the lightweight aggregates were supposed and defined as structural lightweight aggregates leading to a 'high' density value of 1.6 kg/dm^3.

The best mixture performance in fresh state for 20% of replacement, are that mixture that achieve the requirements of porosity, in this case MC AL 20 6, with 28.39% because is the porosity value nearest to the designed value (30%).

Table 14. Fresh state properties of 20% of replacement

Description	Density (kg/dm³)	Porosity (%)
MC AL 20 4	1.54	27.27
MC AL 20 5	1.54	26.81
MC AL 20 6	1.52	28.39
MC AL 20 7	1.42	34.97

Comparing the different mixtures made with 20% of lightweight aggregate with the insulation requirements (Figure 23) it is possible to say that the porosity are in a good range for mixture MC AL 20 6, although, the others mixtures are quite near of the porosity limits.

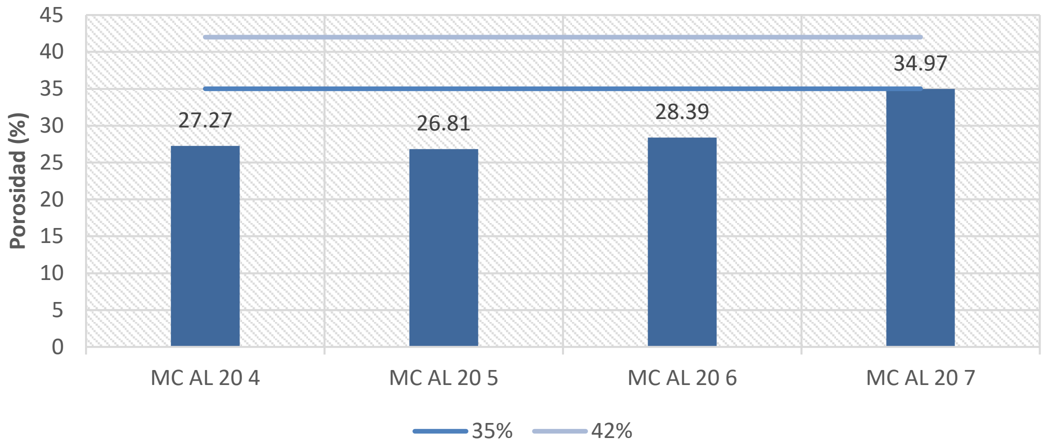


Figure 23. Porosity for mixtures with 20% of lightweight replacement (MC AL 20)

As it was expected, the mixture with high porosity is the mixture with less density (MC AL 20 7 with 1.42 kg/dm^3). The others mixtures are in the range of 27% porosity with density value of 1.5 kg/dm^3.

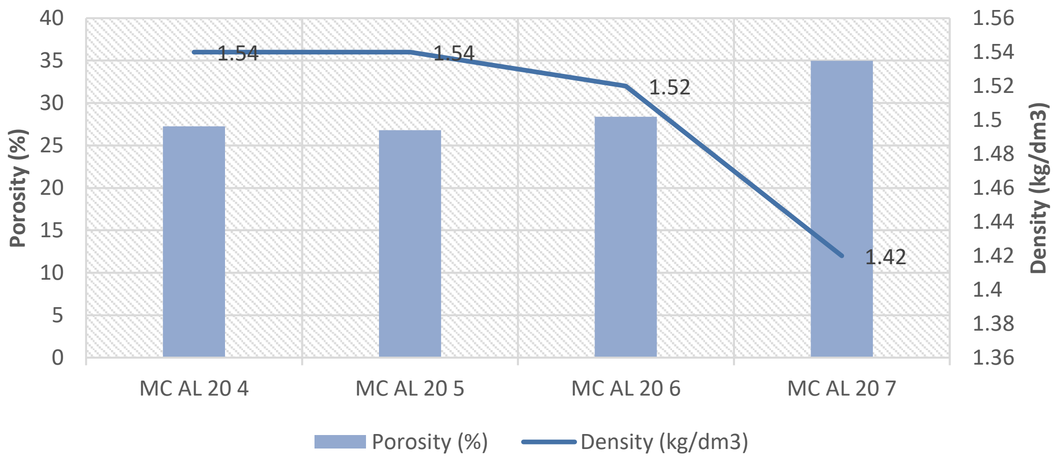


Figure 24. Porosity and density for mixtures with 20% of lightweight replacement (MC AL 20)

Comparing the amount of admixture add in MC (conventional mortar) and in MC AL 20, it is possible to say that is necessary to use more quantity of admixture when lightweight aggregate is used in order to have the same behaviour. With the fresh state properties analysis, the best mixture obtained is MC AL 20 7. This dosage are going to be used in Chapter V for the beams production and the fracture test analysis.

C. Mixtures with 50 % of lightweight aggregate

Based on the mixture with 20% of replacement that achieved the maximum porosity value (MC AL 20 7), the manufacturing process of the mixtures with 50% of lightweight aggregate started based on MC AL 20 7, because at it can be seen in the previous experimental phases, the porosity decrease as the percentage of lightweight aggregate increase. As it was exposed in previous sections, the foaming agent is more effective with natural aggregate. In order to have the same performance with lightweight aggregate is necessary to increase the quantity of the air-entraining admixture.

Table 15. Fresh state properties of 50% of replacement

Description	Density (kg/dm^3)	Porosity (%)
MC AL 50 1	1.46	23.33
MC AL 50 2	1.42	25.48
MC AL 50 3	1.47	22.63
MC AL 50 4	1.53	17.11
MC AL 50 5	1.47	22.58

Table 15 shows that the mixtures made with 50% of lightweight aggregate does not achieve the minimum requirements in terms of porosity. Those fresh state results disable the use of foamed concrete with 50% of lightweight aggregate as an insulation material because does not achieve the minimum value of 30% porosity.

The proportions of the MC AL 50 4 mixture where changed. The w/c ratio was maintained constant, but the amount of cement was increased. Even though with these changes, the dosages still were not suitable for a possible increase in the porosity degree.

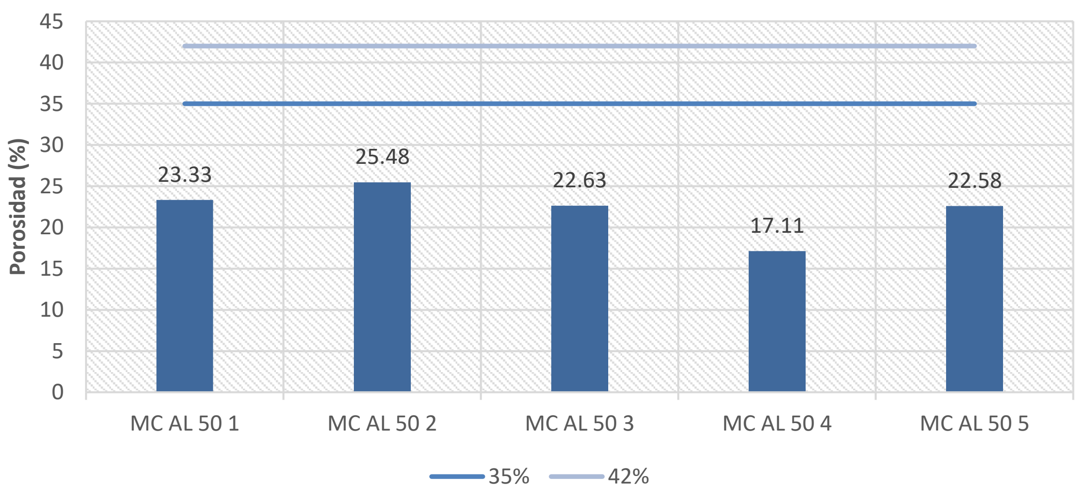


Figure 25. Porosity for mixtures with 50% of lightweight replacement (MC AL 50)

Although, 50% replacement mixtures do not achieve the minimum requirements for porosity (35%-42%), the porosity values obtained in the range of 22% can make these dosages suitable mixtures for other uses, like uses that requires a flowable material.

Providing the amount of air content remained similar, it could be appreciated that the density of foamed concrete also remained similar for mixtures made with 50% of lightweight aggregate.

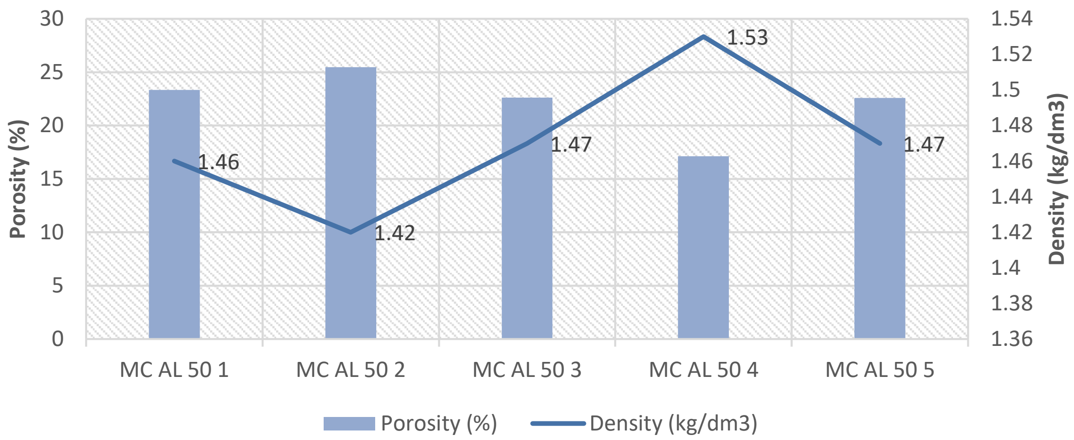


Figure 26. Porosity and density for mixtures with 50% of lightweight replacement (MC AL 50)

As it have been said before, the mixtures made with 50% aggregate replacement are not suitable for the specific goal of this research due to the low porosity values obtained (around 22% when the minimum should be 30%). However, this porosity values still makes a low density material, and for this, there are different kind of applications for this type of material.

D. Mixtures with 100 % of lightweight aggregate

Having analysed all the fresh state properties for 10%, 20% and 50%, it is obvious to realize that the foaming agent good performance decrease as the percentage of lightweight aggregate increase.

Table 16. Fresh state properties of 100% replacement

Description	Density (kg/dm^3)	Porosity (%)
MC AL 100 1	1.51	5.13

For the 10% mixtures it was seen that the influence of the lightweight aggregate were practically negligible, although, and in this case, when making 100% lightweight aggregate mixtures no matter how big is the quantity of the air entraining admixtures that the porosity does not increase, and its less than 6%. This is not strange, if an analysis of the 50% mixtures is done, as it was mentioned, the mixtures achieve a maximum value of 22% of porosity regardless of the amount of admixture added.

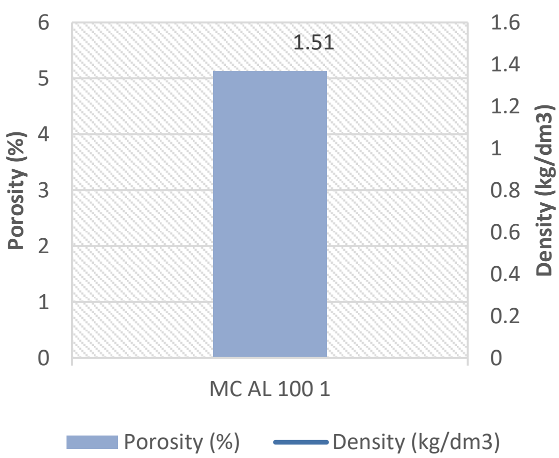


Figure 27. Porosity and density for 100% of lightweight aggregate (MC AL 100)

The maximum value of porosity is 5.13% with a density value of 1.51 kg/dm^3. This features makes the foamed concrete made with 100% of lightweight aggregate unfit for the specific goals of this research that is to achieve an insulation material (high porosity degree) with good hardened state resistance.

Discussion

It can be appreciated that mixtures made with 10% and 100% of lightweight aggregate does not, or hard-won, achieved the required properties for a good insulation and structural foamed concrete. The mixtures with 50% replacement, even with a higher amount of cement and water, also are not suitable for the specific purpose of this research.

However, the mixtures of foamed concrete made with 20% of lightweight aggregate achieved suitable fresh properties for the use of foamed concrete as insulation and structural material, and is for this reason that in the next chapter, the same dosage are going to be done for beams production in order to analyse their fracture resistance.

Hardened state properties

The compressive strength of the mixtures made with 10%, 20%, 50% and 100% of lightweight aggregate are going to be tested in this section. The main objective in this part does not required specific values of compressive strength. In any case, it is necessary to find and optimum balance between porosity and compressive strength, two properties which are inversely related.

It is necessary to analyse the behaviour of the lightweight aggregate and these is examined by analysing the absorption capacity of the sand. The hardened state properties of the mixture are shown in Table 17, Table 19, Table 21 and Table 23.

A. Mixtures with 10 % of lightweight aggregate

Compressive strength

As it has been mentioned above, the mixtures made with 10% of lightweight aggregate hardly achieved independence in the lightweight sand performance. Taking into account that the mixture MC AL 10 1 is practically the same dosage as MC 8.5, except for the 10% of lightweight sand, this non-independence is also corroborated with the compressive strength value which is practically the same in both cases (at 7 days MC 8.5 was 5.88 MPa and MC AL 10 1 was 5.18 MPa).

Table 17. Compressive strength for MC AL 10 mixtures

Description	Compressive strength (MPa)	
	7 days	28 days
MC AL 10 1	**5.18**	**6.92**

Producing mixtures with low replacement percentage, as 10%, makes difficult the analysis of the new aggregate added, is for this that no more mixtures with 10% replacement are going to be done, and the quantity of the substitute aggregate are going to be increased.

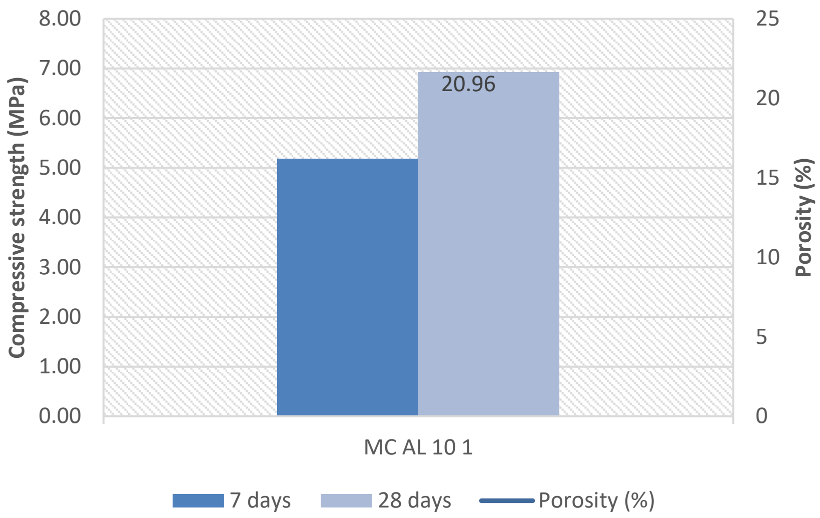


Figure 28. Compressive strength related to porosity for mixtures with 10% replacement

Density, Porosity and Absorption

The dry density of foamed concrete mixture made with 10% of lightweight aggregate is 1.52 kg/dm^3. A comparison of the same dosages between the mixture made with just natural aggregate (MC 8.5) and the mixture made with 10% of lightweight aggregate (MC AL 10 1) is made. The results of both different mixtures are quite similar, confirming what it has been said in the previous sections that a 10% replacement is not a good mixture to analyze the influence of the lightweight aggregate. The porosity is of 15.45%, and the absorption is of a 10.17%. With respect to the values in fresh state, the porosity has decrease a 26%, approximately.

Table 18. Densities, porosity and absorption for MC AL 10 mixtures

	Densities (kg/dm3)				Porosity	Absorption	
	Bulk						
	Dry	Saturated	After boiling	Apparent		Saturated	After boiling
MC AL 10 1	1.52	1.67	1.67	1.80	15.45%	10.17%	10.17%

B. Mixtures with 20 % of lightweight aggregate

Compressive strength

As it is possible to see in Table 19, the mixtures with 20% of lightweight aggregates increase considerably their compressive strength taking into account that the mixtures with just natural aggregate has a similar dosage of the 20% replacement, the compressive strength increase in more than the double.

Table 19. Compressive strength for MC AL 20 mixtures

Description	Compressive strength (MPa)	
	7 days	28 days
MC AL 20 4	**3.32**	**4.64**
MC AL 20 5	**2.35**	**5.30**
MC AL 20 6	**2.66**	**4.07**
MC AL 20 7	**1.36**	**2.68**

The mixture with highest compressive strength is the MC AL 20 5 mixture with a 5.3 MPa. In terms of compressive strength all the mixtures can be suitable for the use of structural material because all of them has higher value than 2.1 MPa that is the limit for a excavable or structural material.

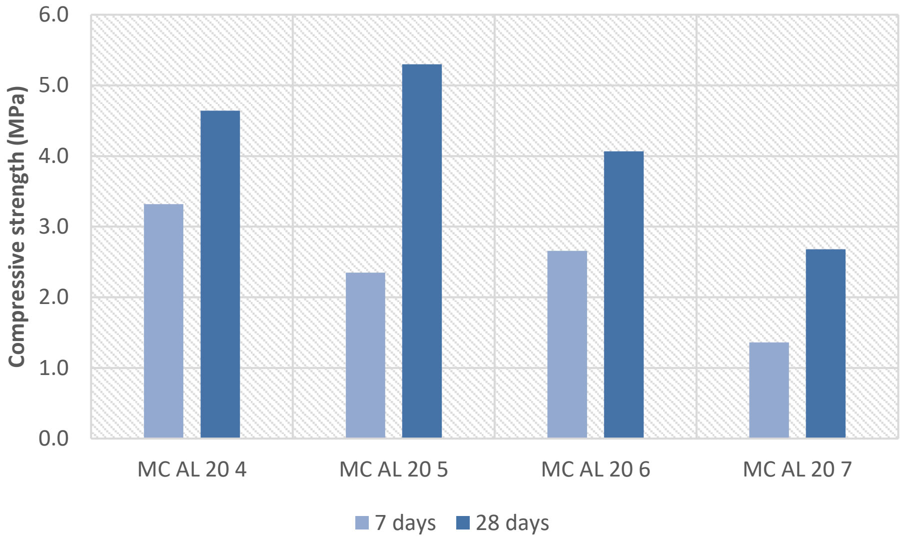


Figure 29. Compressive strength for MC AL 20 mixtures

The best mixture for 20% replacement is the MC AL 20 6 because is the mixture that is nearest the design porosity value (30%). This mixture also are inside the compressive strength values to be consider as a structural material (2,1 MPa < 4,07 MPa < 8 MPa).

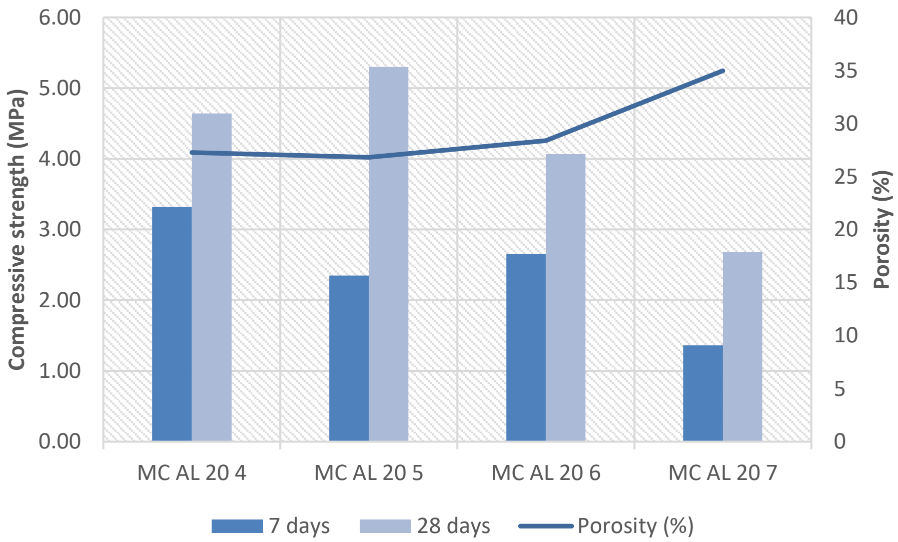


Figure 30. Compressive strength related to porosity for MC AL 20 mixtures

As it possible to deduce from the previous chart, the compressive strength decrease as the porosity of the mixture increase. The pores produce in the structure helps until some point, but from then makes a decrease in the resistance of the test specimens.

Density, Porosity and Absorption

The dry densities of lightweight foamed concrete mixtures made with 20% of lightweight aggregate are in a range between 1.18 and 1.38 kg/dm^3. As it was seen, and also mentioned before, the porosity, in both fresh and hardened state, influence inversely proportional the dry density values. This is a direct effect of the quantity of foaming agent that was increasing while the manufacturing process were taking process in order to increase the porosity value.

Table 20. Densities, porosity and absorption for MC AL 20 mixtures

	Densities (kg/dm3)				Porosity	Absorption	
	Bulk			Apparent			
	Dry	Saturated	After boiling			Saturated	After boiling
MC AL 20 4	1.38	1.57	1.51	1.58	12.51%	13.10%	9.04%
MC AL 20 5	1.40	1.57	1.52	1.59	12.48%	12.69%	8.94%
MC AL 20 6	1.28	1.45	1.49	1.62	20.55%	12.87%	16.00%
MC AL 20 7	1.18	1.33	1.46	1.63	27.87%	13.45%	23.69%

The porosity in hardened state decrease with respect to the porosity in fresh state. However, the same tendency is observed (porosity degree growing, and also total absorption capacity) when increasing the amount of foaming agent. The porosity ranged from 12.48% to 27.87%, and the absorption from 9.04% to 33.69%.

C. Mixtures with 50 % of lightweight aggregate

Compressive strength

Table 21 shows the compressive strength value for the mixtures with 50% replacement. All the mixtures has a water/cement ratio of 0,7. The mixtures 1, 2, 3 and 5 has an amount of water and cement of 175 kg and 250 kg, respectively. However, the mixture number 4 (MC AL 50 4) has and amount of water and cement of 210 kg and 300 kg, respectively. The quantities were change in order to analyze the possible influence in the porosity degree.

Table 21. Compressive strength for MC AL 50 mixtures

Description	Compressive strength (MPa)	
	7 days	28 days
MC AL 50 1	**1.54**	**3.8**
MC AL 50 2	**1.82**	**3.79**
MC AL 50 3	**3.21**	**4.72**
MC AL 50 4	**3.83**	**5.27**
MC AL 50 5	**3.11**	**4.73**

Predictably, the dosage with more quantity of cement is the mixture with highest compressive strength, MC AL 50 4 with 5.27 MPa at 28 days. If just terms of structural properties are taken into account, the whole mixtures made with 50% of replacement can be consider as structural material, because the resistance values are between 2,1 MPa and 8 MPa.

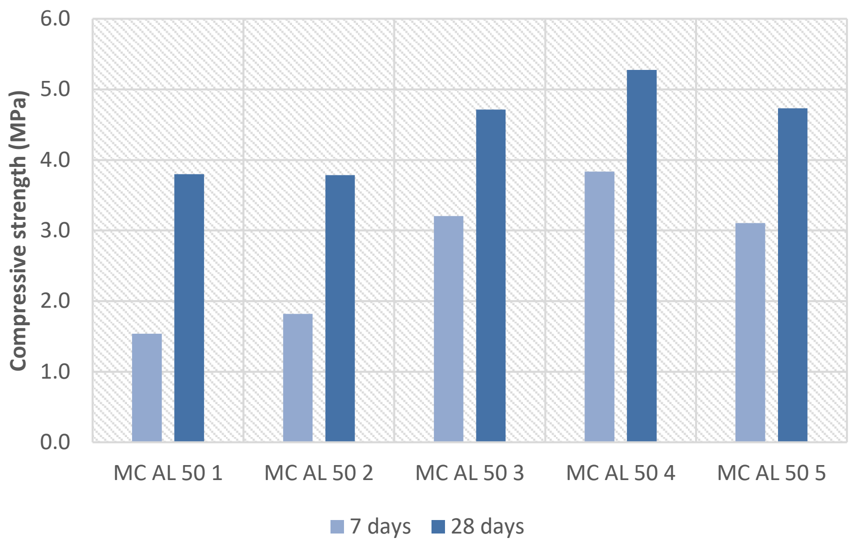


Figure 31. Compressive strength for MC AL 50 mixtures

However, as the main purpose of this research is to find an optimum balance between the porosity degree and the compressive strength value, not all the mixtures are suitable in these terms. The mixture that has the nearest porosity degree as the firstly design, and also has a good resistance values is the MC AL 50 2, with 25.48% of porosity and 3.79 MPa.

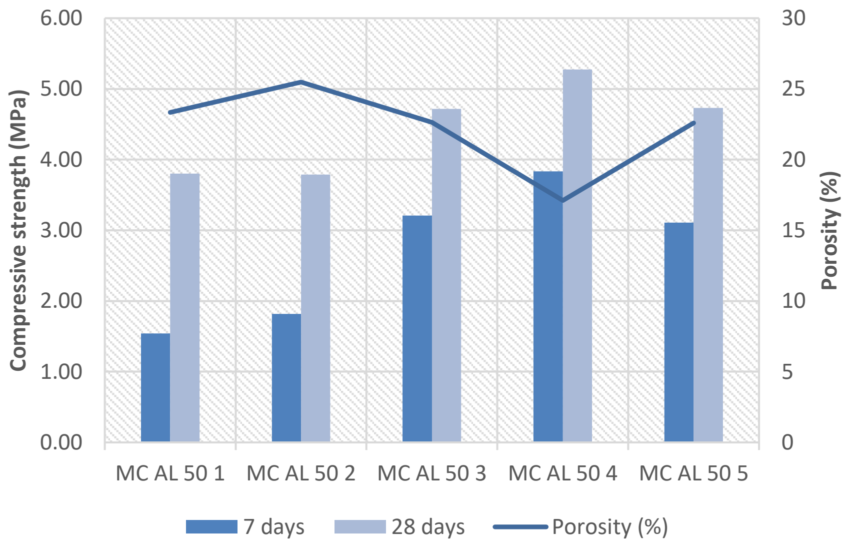


Figure 32. Compressive strength related to porosity for MC AL 50 mixtures

Density, Porosity and Absorption

The dry densities of foamed concrete mixtures made with 50% replacement of lightweight aggregate are in a range between 1.07 and 1.26 kg/dm^3. The mixture with high dry density value is the MC AL 50 4 that has the highest amount of cement (300 kg/m^3). A density value of 1.07 kg/dm^3 is the lowest value achieved until the moment. The purpose of decreasing the density of the mixture by adding lightweight aggregate is being demonstrated with the obtained values.

Table 22. Densities, porosity and absorption for MC AL 50 mixtures

	Densities (kg/dm3)				Porosity	Absorption	
	Bulk						
	Dry	Saturated	After boiling	Apparent		Saturated	After boiling
MC AL 50 1	1.07	1.25	1.35	1.48	27.58%	17.21%	25.78%
MC AL 50 2	1.15	1.34	1.52	1.82	36.39%	16.28%	31.51%
MC AL 50 3	1.17	1.37	1.45	1.62	27.82%	16.97%	23.83%
MC AL 50 4	1.26	1.49	1.51	1.69	25.61%	18.53%	20.41%
MC AL 50 5	1.23	1.44	1.41	1.51	18.77%	17.35%	15.32%

The semi-constant value of the porosity, that the mixtures with 50% of replacement have, says that the foaming agent used (CMX) has a maximum limit after which any increase does not reflect more quantity of air entrained, and so on, the porosity degree does not increase. The total absorption capacity ranged from 15.32% to 31.51%.

D. Mixtures with 100 % of lightweight aggregate

Compressive strength

The resistance of the mixture made with 100% of lightweight aggregate has value of 7.91 MPa, that is a good result because is a value between the lower limit (2.1 MPa) and the upper limit (8 MPa).

Table 23. Compressive strength for MC AL 100 mixtures

Description	Compressive strength (MPa)	
	7 days	**28 days**
MC AL 100 1	**5.08**	**7.91**

However, the porosity value of the 100% replacement mixture is 5.13%, which is an extremely lower value that makes rule out the dosage with that amount of lightweight aggregate. In this case, a more deeply analysis of the lightweight sand influence should be done in order to improve the mixture.

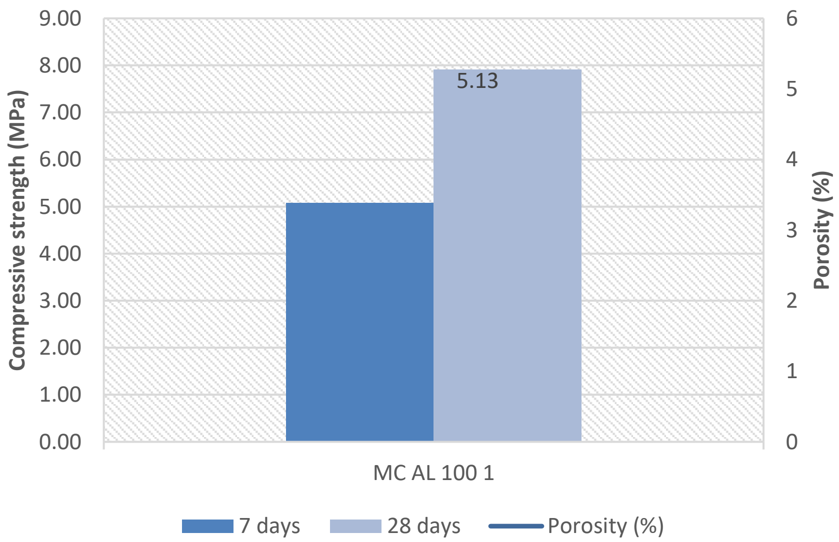


Figure 33. Compressive strength related to porosity for MC AL 100 mixtures

Density, Porosity and Absorption

The dry density of foamed concrete mixture produced entirely with lightweight aggregate is 1.21 kg/dm^3. This density value is higher than the value obtained for the mixtures made with 50% of lightweight aggregate (1.07 kg/dm^3). This can be explained because of the low porosity value that the 100% mixture had (5.13%), almost a null porosity.

Table 24. Density, porosity and absorption for MC AL 100 mixtures

	Densities (kg/dm3)				Porosity	Absorption	
	Bulk						
	Dry	Saturated	After boiling	Apparent		Saturated	After boiling
MC AL 100 1	1.21	1.48	1.45	1.58	23.69%	22.22%	19.59%

The absorption capacity after boiling of the mixture made with 100% of lightweight aggregate is a 19.59%.

4.3. Discussion

The mixtures with 10% of lightweight aggregate does not adequate reflect the influence of lightweight aggregate, is for this, that if the incorporation of low density aggregates should be done, the percentage of sand replaced should be higher than the 10%.

The mixture with 20% of lightweight aggregate represents a suitable insulation and structural material, because has the suitable range of porosity and the compressive strength are in the corresponding ranges. For this, and because the obtained results give proper characteristics in both, fresh and hardened state, there is the possibility of expanding the research in following this line.

The mixtures with 50% of lightweight aggregate does not acquire the minimum requirements to become a structural, and an insulation material. The mixtures with 50% has a good performance in terms of hardened state properties, although, the conditions in fresh state (porosity) are not in the acceptable ranges.

The mixtures with 100% of lightweight aggregates does not perform well with the design dosages. Is for that reason, that further analysis should be done in order to improve the behaviour of the mixtures made with just lightweight aggregate.

CHAPTER V. OPTIMUM DOSAGES FOR BEAMS PRODUCTION

Once and adequate percentage of lightweight aggregate has been defined for the foamed concrete production, more deeply analysis of these mixture was performed in this chapter. The appropriate percentage of lightweight aggregate was a 20%, and this mixture was produce following the previous mixture dosage designed and described as more adequate in the previous section (Chapter IV).

5.1. Introduction

Cracks in concrete, or mortar, have been generally assumed to propagate in the direction normal to the maximum principal stress, which represents the tensile, opening fracture mode, designated as Mode I. This type of cracking has been observed even for the failure of many structures loaded in shear [91]. It has been said for long time that shear fracture does not exist or that 'shear fracture is a sheer nonsense'. However, shear fractures have been experienced. Is for this that this part of the research is very important, above all, for structures subjected to blast, impact, earthquake, and concentrated loads [91].

5.2. Test specimens

Notched beam specimens of lightweight foamed concrete, loaded in the same vertical direction of the notch by a distributed force that produce a concentrated shear force zone, are tested to failure.

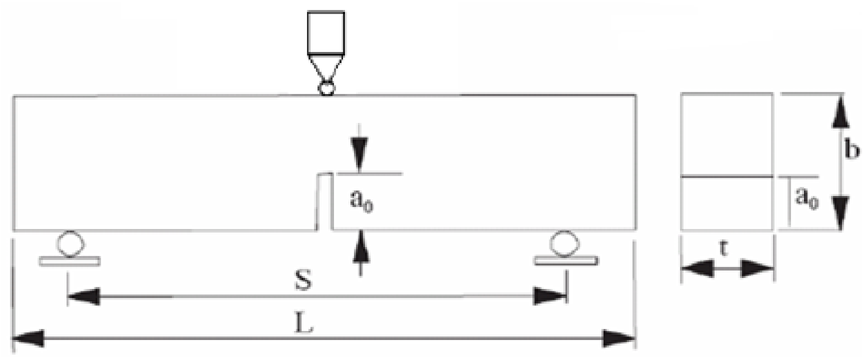


Figure 34. Beam geometry for fracture test analysis

The fracture test had been conducted with the MC AL 20 7 dosage of the mixture previously analysed at stage 2 (Chapter IV). To do so, it was produce two beams of three different sizes shown in Table 25 with constant rectangular cross section and constant length-to-depth ratio.

Table 25. Beams dimensions

Size	d (cm)	L (cm)	l (cm)	a_0 (cm)	b (cm)	Vol (cm^3)
1	3.8	20.3	19.1	2.5	5.1	393.3
2	15.2	40.6	38.1	5.1	5.1	3146.3
3	30.5	81.3	76.2	10.2	5.1	12585.3

Figure 35. Molds used in size 1 (left) and size 2 (right)

The specimens of all sizes were cast from the same lot of foamed concrete lightweight mixture, and their thickness were the same. The aim of using different sizes is to analyze the effect of the probable variation of fracture energy along the crack edge across their thickness. However, for structures of normal sizes, the size of the fracture zone affected by the surface would be proportional to the aggregate size and independent of the specimen size. Therefore, this effect was considered to be more important, and this was the reason for choosing the same thickness for specimens of the three different sizes, ensuring the same thickness-to-aggregate ratio.

Figure 36. Filled molds in size 1 (left) and size 3 (right)

Figure 36 shows the starting point for created the notches, of depth d/6 and thickness 2.5 mm that were done in all the different beams with the same thickness and for all specimen sizes. Figure 37 shows the result of the notches once the beam has acquire their hardened state.

Figure 37. Notches in beams of size 3

Figure 38. Beams already prepared to be tested

The shear loading was produced as a concentrated vertical load, although, with a system of a steel beam, shown in Figure 39, it turns into a distributed load applied onto the specimen. The beam was statically determinate with the applied supports. The steel surface, were carefully machined in order to minimize the friction on the rollers.

Figure 39. Shear loading scheme

5.3. Test results

The cracks do not propagate from the notches in the direction normal to the maximum principal stress but in a direction in which shear stresses dominate. Thus, the failure is due essentially to shear fracture (Mode II) (Figure 40). The crack propagation direction seems to be governed by maximum energy release rate. Tests of geometrically similar specimens yield maximum loads, which agree with the recently established size effect law for blunt fracture, previously verified for tensile fracture (Mode I).

Figure 40. Size 1 specimen after fracture

The cracks were found to propagate as shown in Figure 40. This proves that shear fracture exists, and that the crack propagate in Mode II. The specimens were tested al constant displacement rate of the machine. For each specimen size, the displacement rate was selected (Table 26) to achieve the maximum load in a specific time.

Table 26. Specimens loading rate

Size	**Loading rate** [in/(in/s)]
1. Small	1e-005
2. Medium	2e-006
3. Large	1e-006

This vertically running crack is in the highly stressed zone of the material, and can therefore, cause a large release of strain energy. This appears to confirm that the fracture propagation direction is governed by the criterion of the maximum energy release rate.

Compressive strength were also tested at 7 days in order to determine their specific value from test cylinders that were cast from the batch of lightweight foamed concrete.

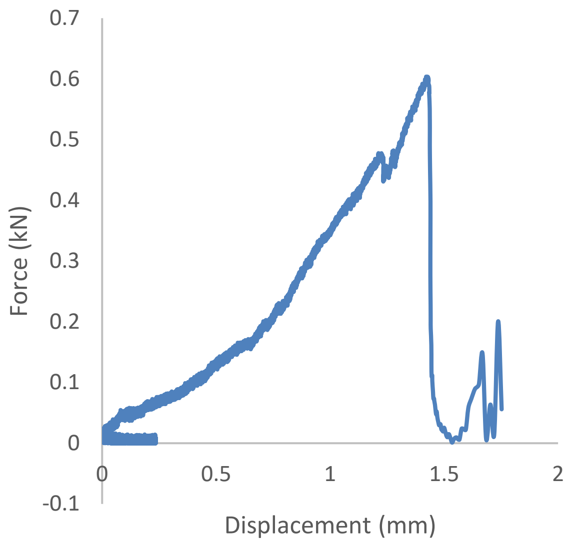
$$f_{ck\ (7\ days)} = 4.3\ MPa$$

However, the most important information from fracture tests is the maximum load measured. Its mean values are given in Table 27 for all the different sizes.

Table 27. Maximum load measured

Size	**Failure load** (kN)
1. Small	0.6
2. Medium	1.16
3. Large	3.21

The following graphs shows the maximum load that each beam size, and each sample, support when testing and charging with some specific failure load.



$$Failure\ load: 0.6\ kN$$

Figure 41. Force-displacement diagram for small beam

Figure 41 represents the force-displacement diagram when the small beam was tested. The most important information is the maximum load capacity before the beam breaks. In this case, the failure load of the size 1 specimen was 0.6 kN.

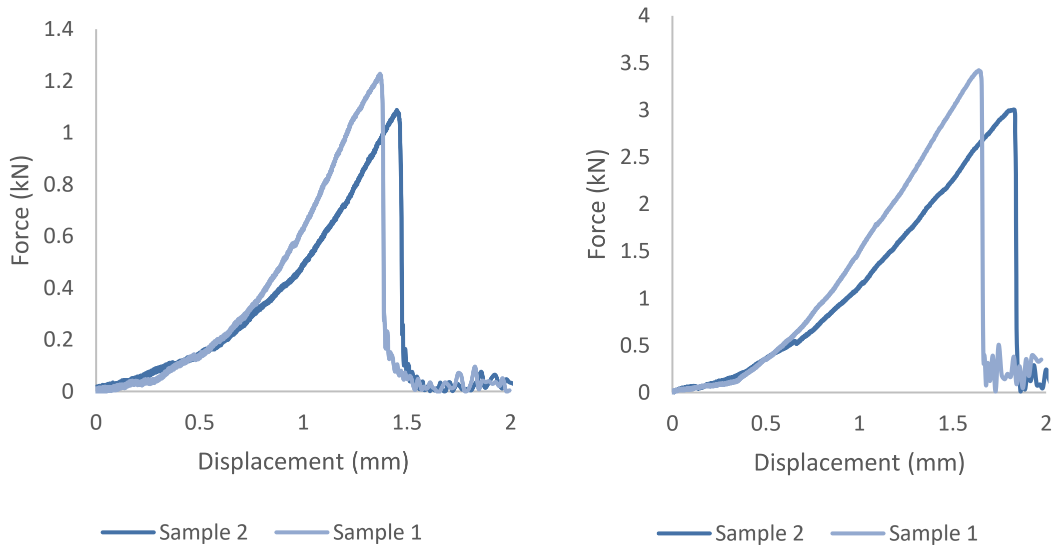


Figure 42. Force-displacement diagram for medium beam (left) and large beam (right)

Figure 42 shows the force-displacement diagram corresponding to size 2 (left) and size 3 (right). The failure load for the medium size beam was 1.16 kN and for the large beam size was 3.21 kN.

$$Failure\ load\ for\ the\ medium\ size\ beam: 1.16\ kN$$

$$Failure\ load\ for\ the\ large\ size\ beam: 3.21\ kN$$

5.4. Discussion

It is demonstrated that shear fracture exists, and like the tensile fracture, the shear fracture follows the effect of direct fracture, which implies that a large fracture process zone must exist at the fracture front. For this, the direction of crack propagation cannot be consider the direction normal to the maximum principal stress. Rather, the fracture shows that propagates in the direction for which the energy discharge.

The maximum principal stresses occur at the notch. Therefore, the cracks are leave from there and propagated internally. This means, that the fracture mode is essentially shear and that the effect of the transverse tensile strain at the middle cannot be significant.

The maximum fracture load change according to the beam size, although, seem to exist a certain fixed multiple that relate the maximum resistance of each beam with the different size, when others characteristics and properties are equal.

CHAPTER VI. CONCLUSIONS AND FUTURE RESEARCH LINES

6.1. Conclusions

6.1.1. Lightweight foamed concrete mixtures

Foamed concrete mixtures made with 10% of lightweight aggregate does not reflect significantly the effect of the low-density sand on their properties. For this, if the goal is to achieve a low-density foamed concrete, the percentage replacement should be higher that 10%.

Foamed concrete mixtures with 20% of lightweight aggregate are good dosages for create an insulation material as well as a structural one. Their properties reach the minimum requirements and has suitable characteristics in both, fresh and hardened state.

Foamed concrete mixtures with 50% or 100% of lightweight aggregate are not a suitable insulation material. The mixtures made with 50% replacement does not achieve the minimum requirements in fresh state, although, in hardened state their properties comply the different requests. The mixtures made with 100% does not achieve the minimum requirements neither in fresh and hardened state.

The mixture made with more quantity of cement show less porosity degree. This is due to the fact that more cement in the mixture provokes foamed concrete structures more closed that makes that the air entrained decrease.

There are some mixtures that despite not surpassing the requirements to be consider as a structural material, can be consider as excavable material, and applications can be found for them.

6.1.2. Lightweight foamed concrete properties

When preparing the dosages it is strongly necessary to take into account the humidity of the lightweight aggregates if the percentage is greater than 0%. For this, the materials should be measured in wet instead of in dry state.

Lightweight foamed concrete can not be defined as a self-compacted material. The experimental phase showed that the compaction of the different mixtures needed from extra energy. The experience lead us to conclude that if a self-compacted material needs to be achieved it is necessary water/cement ratio greater than the unity ($w/c > 1$).

The different properties, as porosity and absorption, acquired lower values in hardened state compared to the values in fresh state, due to their hardening process.

Mixtures made with just natural aggregate when tested to compressive strength, showed a ductile break. However, the mixtures produce with some lightweight aggregate percentage showed a fragile break.

6.1.3. Foaming agents

CMX Concentrate additive is much more stable through time than the Sika Group superplasticizer. Experimental procedures seems to show that CMX give a suitable bubbles size, spacing, and stability for preservation.

The quantity of additive influence directly and proportional the mixtures. However, the additives used has a maximum limit after which any increase does not reflect more quantity of air entrained.

The quantity of additive added in the mixtures with just natural aggregate is of the utmost importance because influence inversely proportional the dry density.

The absorption, porosity and density values vary significantly because of the intervention of the air-entraining admixture in the foamed concrete mixtures. As the amount of additive increase, the porosity and absorption increase and the density decrease.

Compressive strength depends directly, but not exclusively, on the quantity of air entrained. For foamed concrete mixtures, with the same dosage, and keeping all the components equal except for the amount of additive, the compressive strength decrease with the growth of air entrained amount.

6.1.4. Lightweight foamed concrete fracture test

Shear fracture exists and follows the effect of direct fracture, which implies that a large fracture process zone must exist at the fracture front.

The maximum principal stresses occur at the notch. This means, that the fracture mode is essentially shear and that the effect of the transverse tensile strain at the middle cannot be significant.

The maximum fracture load change according to the beam size, although, seem to exist a certain fixed multiple that relate the maximum resistance of each beam with the different size, when others characteristics and properties are equal.

6.2. Futures research lines

Creation of foamed concrete mixes using pre-foam created, this is, instead of adding the amount of admixture directly to the mixture, the pre-foam method is based on preformed the foam independently from the base mix, firstly prepared, and then the foam is added to the mix with the base. It would be necessary to take into account the water inside the foam.

In all the experimental process of this research, the water cement ratio (w/c) was keep constant. However, it would be interesting to experiment with different w/c values. The w/c ratio could influence in the amount of air-entrained, the bubbles distribution and stability. It is a direct and proportional relation, more w/c ratio, more porosity degree, although, in fluid mixtures the air entrained could be unstable with irregular distribution. An optimum balance between those parameters would be the aim of a new research.

As long as it was founded that mixtures made with 20% of lightweight aggregate achieve appropriate properties to be consider as insulation as well as structural material, more research could be done following this line to improve their characteristics.

More research should be done in order to improve the performance of the mixtures made with 50% and 100% of lightweight aggregate. The experimental phase carried out in this research showed that the mixtures with 50% replacement could perform well if some changes or different types of admixtures are used. However, the performance of the 100% lightweight foamed concrete seem to be more difficult.

Tracing of the different mixtures produced making stability test in order to ensure that the material maintain during its hardening process their volume.

Analysis of the relation between the maximum fracture load of a beam with their size, while the others properties remain constant.
According also with fracture test analysis, the relation between the fracture energy for shear and tensile test. This would be interesting because shear fracture energy not also require the energy to create inclined tensile micro-cracks, but also the energy to break the shear resistance due to the aggregate and the cement matrix.

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APPENDICES

APPENDIX I: TECHNICAL INFORMATION OF FOAMING ADMIXTURE

RICHWAY
CMX Foam Concentrate

Formulated in house specifically for use in cellular concrete production. Works well for all densities of cellular concrete.

Foaming agents for the production of cellular concrete are either protein based or synthetic based materials.

Richway produces only synthetic based foam concentrates. They offer much longer shelf life, have no obnoxious odor, and perform well under a variety of conditions. Desired foam life, water quality, (including hardness, water temperature, and other materials in the water) and other factors are important in selecting a foam concentrate.

CreteFoam CMX is proven in a wide range of cellular concrete applications. There are many factors in achieving quality cellular concrete material. Having the right foam concentrate is one of them. CMX performs with higher carbon contents, tough placements conditions, and is proven to withstand higher lifts.

With over 40 years of foam concentrate formulation development, manufacturing, and testing, Richway is able to provide superior foam concentrate for all of your cellular concrete applications.

Bubble size, an important variable in compressive strength of cellular concrete is determined by both the foam generation equipment and the foam concentrate used.

CRETEFOAMER™
Cellular Concrete Equipment

Complies with all Specifications of ASTM C869

APPENDIX II: TECHNICAL INFORMATION OF SUPERPLASTICIZER

Product Data Sheet
Edition 10.10.2014
Sika® ViscoCrete®-2110

Sika® ViscoCrete®-2110

High Range Water Reducing Admixture

Concrete

Description	Sika® ViscoCrete®-2110 is a high range water reducer and superplasticizer utilizing Sika's ViscoCrete® polycarboxylate polymer technology. Sika® ViscoCrete®-2110 meets the requirements for ASTMC-494 Types A and F and AASHTO M-194 Types A and F admixture.
Applications	Sika® ViscoCrete®-2110 may be used in both ready mix and precast applications, as a plant added high range water reducer to provide excellent plasticity while maintaining slump for up to 90 minutes. Controlled set times make Sika® ViscoCrete®-2110 ideal for horizontal and vertical applications. Sika® ViscoCrete®-2110 is ideal for production of Self Consolidating Concrete (SCC).
Benefits	Sika® ViscoCrete®-2110 can be used for all levels of water reduction in various types of concrete ranging from dry cast applications, conventional concrete to SCC (Self Consolidating Concrete). Sika® ViscoCrete®-2110 will deliver water reduction up to 45%. The special formulation of Sika® ViscoCrete®-2110 increases compressive strength of concrete and helps maintain the plasticity of the concrete over prolonged period of time. Sika® ViscoCrete®-2110 extends concrete workability time during warmer months when slump loss and fast stiffening of the fresh concrete can be a concern. The superplasticizing action of Sika® ViscoCrete®-2110 provides high slump / flowing concrete that be placed with minimal or no vibration even at very low water cementitious ratios, as low as 0.25. **Water Reduction:** Sika® ViscoCrete®-2110 can be dosed in small amounts to obtain water reduction from 10-15%, and will achieve water reduction up to 45% at high dosage rates. Sika® ViscoCrete®-2110 is suitable for all levels of water reduction. **Plasticizing effect:** The superplasticizing action of Sika® ViscoCrete®-2110 provides high slump, flowing concrete that maintains excellent workability and may be placed with minimal vibration even at very low water cementitious ratio's as low as 0.25. Sika® ViscoCrete®-2110 plasticized concrete is highly fluid while maintaining complete cohesion within the concrete matrix to eliminate excessive bleeding or segregation. **Extended Slump Life and Set Control:** Sika® ViscoCrete®-2110 has been formulated to provide controlled and predictable extended slump life for periods of 60 to 90 minutes with normal set times. The combined high range water reduction and superplasticizing action of Sika® ViscoCrete®-2110 provide the following benefits in hardened concrete: Higher ultimate strengths allow for greater engineering design flexibility and structural economies. Reduced water cement ratios produce more durable, dense concrete with reduced permeability. Highly effective plasticizer reduces surface defects in concrete elements and improves aesthetic appearance. Sika® ViscoCrete®-2110 has been formulated to provide maximum water reduction and extended slump retention throughout entire dosage range. ■ Extended slump life. ■ Increased compressive strength when compared to reference concrete with same w/cm ratio. ■ High early compressive strengths for earlier removal of forms and structural use of concrete. ■ High ultimate strengths allow for greater engineering design flexibility and structural economies. ■ Reduced water cementitious ratios produce more durable, dense concrete with reduced permeability. ■ Highly effective plasticizer reduces surface defects in concrete elements and improves aesthetic appearance. ■ Ideal for the production of Self Consolidating Concrete.

APPENDIX III: TECHNICAL INFORMATION OF CLIP-ON GAUGE FOR FRACTURE TEST